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IMPRESSED CURRENT CATHODIC PROTECTION (ICCP) PHYSICAL SCALE MODELLING (PSM) AND CPBEM MODELLING OF CANADIAN PATROL FRIGATE (CPF) HULL POTENTIAL PROFILES

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Defence R&D Canada

**Contractor Report
DREA CR 2001-014
February 2001**



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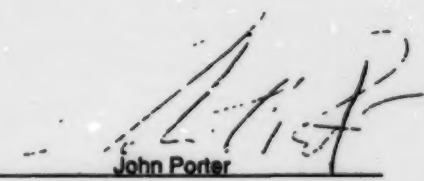
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DREA CR 2001-014

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PHYSICAL SCALE MODELLING (PSM) AND
CPBEM MODELLING OF CANADIAN PATROL
FRIGATE (CPF) HULL POTENTIAL PROFILES**

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W7707-9-7301
Contract Number

February 2001

CONTRACTOR REPORT

Prepared for

Defence
Research
Establishment
Atlantic



Centre de
Recherches pour la
Défense
Atlantique

Canada

UNCLASSIFIED

**Impressed Current Cathodic Protection (ICCP)
Physical Scale Modelling (PSM) and
CPBEM Modelling of Canadian Patrol Frigate (CPF)
Hull Potential Profiles.
Final Report
Contract No. W7707-9-7301**

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ABSTRACT

A comprehensive program was conducted to develop two independent methodologies for generating hull potential profiles for impressed current cathodic protection systems. The two methodologies developed were physical scale modeling and computer simulations using CPBEM and BEASY software suites. Conducting the physical scale modeling trials required upgrading the previously inactive PSM facility. The upgrades included designing and developing a digital communication protocol for the system, controllers for the PSM analog devices and controllers for the ICCP model. A 1/100 scale model of CPF was fabricated and instrumented for comparison with the computer simulations. The results indicated that both CPBEM and BEASY computer simulations were in good agreement with the potentials generated by the PSM/ICCP model. For the quiescent tests conducted, the potentials predicted by CPBEM and BEASY were generally within 5 percent and 2 percent of the PSM potentials, respectively. For the dynamic tests conducted, both CPBEM and BEASY produced potentials within 5 percent of the PSM potentials.

RÉSUMÉ

Un programme complet a été exécuté dans le but de mettre au point deux méthodes indépendantes pouvant générer des profils de coque possibles pour des systèmes de protection cathodique par courant imposé (PCCI). Les deux méthodes mises au point faisaient appel à la modélisation d'échelle physique (MEP) et à des simulations informatiques à l'aide des suites de logiciels CPBEM et BEASY. Les essais de modélisation d'échelle physique ont exigé la mise à niveau des installations MEP, qui demeuraient auparavant inactives. Cette mise à niveau comprenait la conception et la mise au point d'un protocole de communication numérique pour le système, les contrôleurs des dispositifs analogiques de MEP et les contrôleurs du modèle de PCCI. Un modèle à l'échelle 1/100 de la FCP a été constitué et doté d'instruments afin de permettre les comparaisons avec les simulations informatiques. Les résultats ont indiqué que les simulations informatiques de CPBEM et BEASY s'accordaient bien avec les profils possibles du modèle MEP/PCCI. En général, les essais au repos ont révélé que les profils possibles générés par CPBEM et BEASY se situaient respectivement à au plus 5 pour cent et 2 pour cent des profils possibles de MEP. Dans le cas des essais dynamiques, CPBEM et BEASY indiquaient tous deux des profils possibles ne s'écartant pas de plus de 5 pour cent des profils possibles de MEP.

DREA CR 2001-014

**Impressed Current Cathodic Protection (ICCP) Physical Scale Modelling (PSM)
and CPBEM Modelling of Canadian Patrol Frigate (CPF) Hull Potential Profiles**

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EXECUTIVE SUMMARY

Introduction

Paint and preservation systems, combined with impressed current cathodic protection (ICCP) are the mainstay of corrosion prevention measures for Canadian Naval platforms. The design of ICCP systems remains predominately based upon empirical relationships and engineering judgement. Owing to these inexact methods, many CF hull form ICCP systems have required modifications to correct various deficiencies. To overcome these design deficiencies, DREA designed and fabricated a physical scale modelling (PSM) test facility to experimentally determine hull potential profiles under static and dynamic conditions. Boundary element numerical modelling software (CPBEM), to simulate the operation of ICCP systems and determine hull potential profiles was also developed. The present multi-phase development program was commenced to build upon these capabilities to establish design/maintenance protocols for naval platform ICCP systems. The attached contract report (DREA CR 2001-014) documents the activities of the first two phases of this development program.

Results

In the first phase of activities (W7707-8-6404), the PSM facility was upgraded to include a digital communication protocol, controllers for the PSM analog devices and controllers for the CPF ICCP model. Potentio-dynamic polarization resistance curves were generated for nickel aluminum bronze under static and dynamic conditions. In the second phase of activities (W7707-9-7301), the PSM and CPBEM methodologies were refined and applied for the generation of ICCP hull potential profiles. A 1/100 scale CPF physical scale model was fabricated and instrumented. Experimental hull potential profiles were obtained using fluid velocity and anode placement as the variables. CPBEM was modified to incorporate fluid velocity effects on the predicted hull potential profiles. CPBEM and the commercial code BEASY were both applied to simulate CPF hull potentials, employing similar conditions as the model employed in the PSM facility. For the quiescent tests, the hull potentials predicted by CPBEM and BEASY were within 5% and 2% respectively of the PSM results. For the dynamic tests, the hull potentials predicted by CPBEM and BEASY were both within 5% of the PSM results.

Future Plans

The objective of the next phase of the development program includes further refinement and application of PSM and CPBEM capabilities for the generation of CPF ICCP hull potential profiles. The PSM facility and the associated instrumentation will be enhanced to address the deficiencies identified in the earlier phases. Long term polarization resistance curves for NAB, required for the accurate analytical analysis of the hull potential profiles, will be developed during this phase. CPBEM will improve its ability to incorporate fluid velocity effects on the hull potential profiles. The PSM potential profiles will be compared to the CPBEM profiles, generated under the same fluid velocity and anode placement. The influence of protective coating integrity will be simulated both experimentally and numerically and discrepancies between the two independent test methodologies will be addressed.

Prepared by: J.F. Porter, GL/MM(A)

CRDA CR 2001-014

Modélisation d'échelle physique (MEP) et modélisation CPBEM des profils de potentiel de coque de la Frégate canadienne de patrouille (FCP) pour des systèmes de protection cathodique par courant imposé (PCCI)

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SOMMAIRE

Introduction

Les systèmes de peinture et de préservation, combinés à la protection cathodique par courant imposé (PCCI), constituent les principaux moyens de prévention de la corrosion pour les plates-formes navales canadiennes. La conception des systèmes de PCCI demeure essentiellement fondée sur les relations empiriques et le jugement technique. Étant donné l'inexactitude de ces méthodes, beaucoup de systèmes de PCCI utilisés pour les coques des FC ont nécessité des modifications pour corriger différents défauts. Afin de remédier à ces défauts de conception, le CRDA a conçu et fabriqué des installations de modélisation d'échelle physique (MEP) pour déterminer de façon expérimentale les profils de potentiel de coque dans des conditions statiques et dynamiques. Un logiciel de modélisation numérique d'éléments de contour (CPBEM), servant à simuler le fonctionnement des systèmes de PCCI et à déterminer les profils de potentiel de coque, a également été mis au point. L'actuel programme de développement à phases multiples a été mis sur pied dans le but d'établir, en tirant profit de ces ressources, des protocoles de conception/maintenance des systèmes de PCCI des plates-formes navales. Le rapport d'avancement ci-joint (CRDA CR 2001-014) décrit les activités des deux premières phases de ce programme de développement.

Résultats

Durant la première phase des activités (W7707-8-6404), les installations de MEP ont été améliorées de façon à inclure un protocole de communication numérique, des contrôleurs pour les dispositifs analogiques de MEP et des contrôleurs pour le modèle de PCCI de la FCP. Des courbes de résistance de polarisation potentiodynamique ont été tracées pour le bronze au nickel-aluminium dans des conditions statiques et dynamiques. Au cours de la deuxième phase d'activités (W7707-9-7301), les méthodes MPE et CPBEM ont été raffinées et appliquées à la production de profils de potentiel de coque de PCCI. On a fabriqué un modèle d'échelle physique 1/100 de la FCP et mis en place les instruments nécessaires. Les profils de potentiel de coque obtenus expérimentalement se fondaient sur les variables de vitesse des fluides et de positionnement d'anode. Le programme CPBEM a été modifié pour prendre en compte les effets de vitesse des fluides sur les prévisions

des profils de potentiel de coque. Le programme CPBEM et le logiciel BEASY à code commercial ont tous deux servi à simuler des potentiels de coque de la FCP, dans des conditions semblables à celles du modèle employé dans les installations de MEP. Lors des essais au repos, les potentiels de coque prévus par les programmes CPBEM et BEASY se situaient respectivement à au plus 5 % et 2 % des résultats de la MEP. Lors des essais dynamiques, les potentiels de coque prévus par les programmes CPBEM et BEASY se situaient tous à au plus 5 % des résultats de la MEP.

Plans pour l'avenir

L'objectif de la prochaine phase du programme de développement consiste à améliorer encore les ressources de MEP et de CPBEM et d'appliquer ces ressources à la production des profils de potentiel de coque de PCCI de la FCP. Les installations de MEP et les instruments connexes seront perfectionnés pour prendre en compte les défauts détectés durant les phases précédentes. Les courbes de résistance de polarisation à long terme du bronze au nickel-aluminium, nécessaires à une analyse précise des profils de potentiel de coque, seront établies au cours de cette phase. Le programme CPBEM deviendra mieux à même de prendre en compte les effets de vitesse des fluides sur les profils de potentiel de coque. Des profils de potentiel de MEP seront comparés à des profils de CPBEM, générés dans les mêmes conditions de vitesse des fluides et de positionnement d'anode. L'influence de l'intégrité du revêtement protecteur sera simulée, selon des méthodes expérimentales et numériques, et les divergences entre les deux méthodes d'essai indépendantes seront examinées.

Préparé par : J.F. Porter, GL/MM(A)

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1. INTRODUCTION

1.1 General

Paint and preservation combined with cathodic protection is the mainstay of preventative measures employed by the Canadian Navy for the interior and exterior corrosion protection of marine hull forms. The Canadian Navy has historically been a world leader in the development of innovative hardware for marine based cathodic protection systems. However, the design of these cathodic protection (CP) systems is still based on past experience, empirical relationships and engineering judgement. Owing to this inexact method of designing CP systems, a majority of the systems designed for CF hull forms have required modifications to correct various deficiencies. These deficiencies lead to increased current requirements (which exacerbate ship signature problems) in order to adequately protect the hull. Also, empirical design often results in areas of over protection and under protection which leads to increases in long term maintenance costs.

A typical cathodic protection system consists of three parts; the structure to be protected (cathode), the anode which provides the protection, and the electrolyte (i.e. seawater). There are two general types of anodes in normal use; sacrificial and impressed current. Sacrificial anodes are usually made of zinc, aluminum alloys, magnesium, or similar materials that are more active in the galvanic series than iron or steel. The sacrificial anode corrodes in place of the protected structure. By contrast, impressed current anodes apply a potential difference by means of an external power supply.

The overall objective of this tasking is the development of comprehensive design/maintenance protocols for specifying and upgrading interior and exterior cathodic protection systems. These protocols will be established by employing the quantitative tools which have already been partially developed at the DRE's. A significant amount of R&D targeted at achieving the goal has already been completed. Over the past five years, DREA has been developing the tools to quantitatively assess hull potentials associated with cathodic protection systems. Studies at DREA indicate the suitability of the boundary element method for analytical mapping of hull potentials for externally mounted impressed current systems. DREA developed an accurate, portable, analytical system for mapping impressed current potentials (CPBEM). This model was verified by conducting a static sea trial of the CPF hull form. Subsequent development by DREA resulted in an enhanced graphical user interface to allow corrosion engineers to use the system as a tool to look for deficiencies in ICCP systems. An out of core solver was also incorporated so that the number of elements would not restrict the model size.

DREA currently maintains a physical scale model (PSM) test facility. The PSM system's primary function is to develop an independent technology to provide hull potential profiles under static and dynamic conditions. Physical scale modelling can also be used for the verification of the computational models.

The focus of this study is to develop two independent methodologies for the generation of ICCP hull potential profiles. The first task focuses on developing the physical scale model and the instrumentation associated with conducting the testing. Also, polarization resistance curves for

nickel aluminum bronze (NAB), which are required for the accurate computer modelling of the hull potential profiles, are developed during this phase. In the final stages of this task, experimental data (hull potential profiles) are obtained using fluid velocity and anode/reference electrode configuration as the variables. The second tasking focuses on modifying the current analytical CPBEM software to incorporate fluid velocity effects on the hull profiles. The PSM potential profiles generated are compared to the CPBEM profiles generated under the same fluid velocity and anode/reference electrode configurations.

1.2 Physical Scale Modelling

Physical scale modelling of cathodically protected marine structures provides acceptable approximations of global hull potential profiles. It has been shown that large structures subjected to cathodic polarization can be physically modelled by maintaining a linear relationship between the model size (ie 1/100 scale) and electrolytic medium conductivity. As a first approximation, the hull form is modelled as a perfectly coated system (ie electrically insulating). This is usually accomplished by fabricating the hull of the model from insulating materials such as FRP or PVC. In this configuration, polarization of the uncoated propeller surface area accounts for a majority of the current demand from the ICCP system.

The anode current required to protect the hull increases as hull velocity increases. Under normal service conditions, this is the result of the increased rate of oxygen transfer to the cathodic surfaces. Incorporating hull velocity effects into physical scale modelling is usually accomplished by dimensionally modelling fluid velocity.

The Canadian Patrol Frigate (CPF), the structure of interest for this study, is cathodically protected using a two zone impressed current system. The forward zone consists of two impressed current anodes with a controlling reference electrode located forward with respect to the anodes. The stern zone is again comprised of two anodes located in front of the propellers with the reference electrode controlling the anodes located aft of the propellers (designated as aft-aft). Optionally, the aft anodes can be controlled using a reference electrode (designated as mid-aft) located between the forward and aft anodes. While both zones are controlled independently from each other, potential fields interact throughout the center portion of the ship. For this study, replication of the CPF control system is proposed. The system will be configured with two independently controlled zones with PID logic controlling anode currents based on predetermined reference electrode potentials. Also, several non-controlling reference electrodes will be located along the axis of the model to provide a more detailed map of the global hull potential profile.

Analytical modelling requires electrochemical data for the relevant materials systems as part of the input data. The relevant information required is generated by conducting polarization resistance measurements for the relevant material systems under service conditions. In the case of CPF, the hull form is coated 350 WT and the propellers are manufactured from NAB. The propellers are left uncoated and thus generate the majority of the current requirements for the aft

zone of the system. Hull velocities can range from static conditions to approximately 30 knots. The kinetics of the reactions governing the polarization resistance of these materials are dependent on velocity of the seawater passing along the hull and over the propellers. It therefore becomes necessary not only to produce static polarization curves, but also dynamic polarization resistance curves for these materials. Physical scale modelling systems can be used to facilitate the generation of this data.

1.3 Computer Modelling

Metal structures will corrode in aggressive environments if they are left unprotected. Although surface coatings will inhibit the corrosion process, for long term protection a cathodic protection system with sacrificial anodes or impressed anodes is generally used. These systems set up an electrostatic field in the electrolyte (ie sea water) thus protecting the structure from corrosion if the correct level of the electrical potential is achieved.

The task of a designer of an impressed current cathodic protection system is to determine the location and capacity of the anodes so that the whole structure is protected efficiently. The design can significantly affect the useful life-time of a structure. Poor designs can be far more costly to implement than optimal designs. Improper design can cause overprotection, with resulting paint blistering and accelerated corrosion of some alloys, or under protection, with resultant structure corrosion or stray current corrosion of adjacent structures.

A number of investigators have been applying various computational methods to the design of cathodic protection systems. The basic mathematical problem is defined by the Laplace equation and is straightforward to solve. However, some problems are typically encountered in modelling cathodic protection systems under actual service conditions. The hull coatings undergo gradual degradation over time with the result that they become progressively less effective as electrical insulators. This is particularly true in the propeller area where there are concerns about availability of reliable polarization curves, variability of seawater conductivity, and finite paint resistance. Another area of uncertainty is the dynamic conditions of ship operations.

BEASY-CP, a software program developed and marketed by Computational Mechanics Inc. of Billerica, Maine and the CPBEM program developed by DREA Dockyard are two typical software packages that can be used by the designer to predict the potential levels both on a structure and in the electrolyte and to determine the current levels on the structure and anodes. Martec Limited has been involved in work for the Canadian DND using both of these software packages. However, all of this prior simulation work has involved static conditions. One of the objectives of this study is to consider the effects of dynamic conditions on cathodic protection systems.

The analysis problem under consideration will be the prediction of the electric potential distribution in an electrolyte medium due to the presence of submerged dissimilar metals or externally applied impressed currents. The conservation of charge within an electrolyte is the

basis of the mathematical formulation used in cathodic protection analysis. The governing equilibrium equation reduces to the Laplace equation expressed in terms of the electrical potential for certain idealized conditions. The Laplace equation is valid for steady state conditions, a uniform homogenous electrolyte, and no charge sources or sinks in the electrolyte.

Numerical methods, including finite difference, finite element and boundary element methods, have been utilized to solve the Laplace equation in heat transfer and (hydrodynamic) potential flow applications. Program developers interested in cathodic protection problems have adapted these numerical methods by providing for appropriate boundary conditions and variable definitions. For an impressed current cathodic protection system, the flux (current) on the anode surface is constant. On well painted surfaces, the flux is assumed to be zero. The flux on the cathodic surface is proportional to the difference between the potential in the electrolyte, and the equilibrium potential of the electrode, with a proportionality factor that represents the cathodic polarization function. While numerical solutions are possible with linear representations for the cathodic polarization function, this has been recognized as being an oversimplification. The current polarization relationship is affected by surface condition and treatment, temperature, and other environmental factors. The relationship is often nonlinear thus requiring increasingly sophisticated algorithms to converge the solution.

A detailed discussion of the Laplace equation and the boundary conditions as applied to cathodic protection and galvanic corrosion analysis can be found in publications by Zamani et al. [1,2] and Brebbia and Dominquez [3]. An excellent state-of-the-art survey article outlining the development of finite difference, finite element and boundary element methods for galvanic analysis has been prepared by Munn [4]. The relative capabilities and limitations of the three methods were outlined. The advantage of the finite difference method is its reduced storage requirements but its disadvantage is that curved or oblique boundaries cannot be readily accommodated. Because of the flexibility of its element shapes and orientations, the finite element method is more suitable for problems with complex geometries or with inhomogeneous material (electrolyte) properties. The main disadvantage is its inability to represent infinite domains. The boundary element method provides direct solutions for boundary points only (solutions at other points are obtained as a post-processing step) and for that reason is more suitable for modelling infinite domains. Its advantage over finite element methods reduces as domain boundary complexity increases.

Zamani and coworkers developed the CPBEM program based on the boundary element method for the assessment of galvanic corrosion system behaviour under contract to the DREA Dockyard Laboratory [2]. In the application of the program to a prototype ship, the propeller was treated as the cathodic area while the hull shell was assumed painted and thus perfectly insulated (no current). Predicted protection levels for prescribed anode configuration and current levels were within 15% of those measured on a full-scale ship. Following the initial development of the CPBEM program, engineers at Martec Limited supplied a pre-processor and post-processor for the program with the result that the program became much more user friendly [5]. These processors greatly simplified the task of preparing input data for and reviewing output

from CPBEM. The pre-processor (CPBGEN) is a model generator that takes as input the hull shape offsets and creates a geometric description of the submerged portion of a ship hull, including anode locations, which is then converted into a CPBEM model. Since CPBEM can take advantage of the symmetric characteristic of a ship hull in the analysis, CPBGEN generates models only for one side of the hull. The only shape restrictions are that the submerged hull be symmetric, that there be no slope discontinuities in the symmetric description of submerged hull shape, and that the aft end of the submerged hull be blunt.

Other improvements included more precise modelling of the propeller that serves as a cathode. Originally, the propeller was approximated by an arbitrary strip of boundary element panels at the aft end of the ship hull. These panels collectively had approximately the same area as the surface area of the propeller blades. The strip form of the cathode provided a reasonable approximation of the potential current densities everywhere except in aft portions of the ship near the cathode strip. Unfortunately, in practice some severe corrosion problems develop in that area of the ship hull [6]. Consequently, the propeller strip was replaced by an approximation of an actual propeller in order to improve the resulting potentials on the portion of the hull near the propeller. Two forms of propeller approximation were considered. The simpler of the two was a disk that was approximately equivalent to the actual propeller. This type of propeller model was used by De Giorgi et al. [7]. The second propeller approximation was a detailed propeller model with five distinct blades. Both approximations showed conditioning problems as blade thickness was decreased which necessitated the implementation of a hypersingular boundary element formulation within CPBEM. In the second propeller approximation, some simplification in the shape of the propeller blades was also required in order to achieve convergence.

Recently, Martec has investigated the feasibility of using BEASY-CP to assess the electric fields produced by naval surface ships [8]. A variety of boundary element models were developed to evaluate the software, including example problems of simple cathodic protection system configurations. These configurations included a barge protected with sacrificial anodes for which experimental data was available, and the impressed current cathodic protection system of the Canadian Patrol Frigate. Comparisons of the model results to experimental or other numerical results show that BEASY-CP can accurately simulate cathodic protection systems. The program is robust. However, these investigations pointed out some limitations of BEASY-CP for prediction of electric fields around naval vessels.

2.0 HARDWARE/SOFTWARE DEVELOPMENT

2.1 General

Previous to this study, the ICCP/PSM facility remained inactive for an extended period. Thus prior to configuring the system to perform the tasks required, the facility was reduced to its component level. On the seawater side, valves and sensors were checked for evidence of biogrowth buildup (ie mussels, algae) and, if present, the biogrowth was removed before reassembly. The mechanics (ie gears and motors) of the remotely actuated valves were also inspected for evidence of degradation. It was noted that several of the plastic gears on valve actuator stems are beginning to show signs of cracking and should be periodically inspected and replaced as the cracking becomes significant. The stability of the internal feedback control loop in each remotely actuated valve was checked by individually connecting the required AC power source to the valve and then connecting various levels of stable DC signal (1.5VDC , 6VDC, 9VDC) to the input command port. Each valve was monitored for several hours while connected in these configurations for "mechanical jittering" which would indicate evidence of electronic problems in the feedback control circuits. Two of the ten valves showed evidence of electronic instability. In one valve, it was determined that the actuator drive motor required repair, and in a second valve, one of the feedback control circuits showed evidence of electrical arcing. Because the proposed configuration of the ICCP/PSM facility requires only nine valves (as opposed to the ten in the current configuration), functioning components from the two valves which showed electronic instability problems were combined into one valve. The valve with the non-functioning components was returned to DREA/DL. Figure 2.1 is a schematic representation of the PSM facility configuration used to conduct the ICCP modelling test trials for this study.

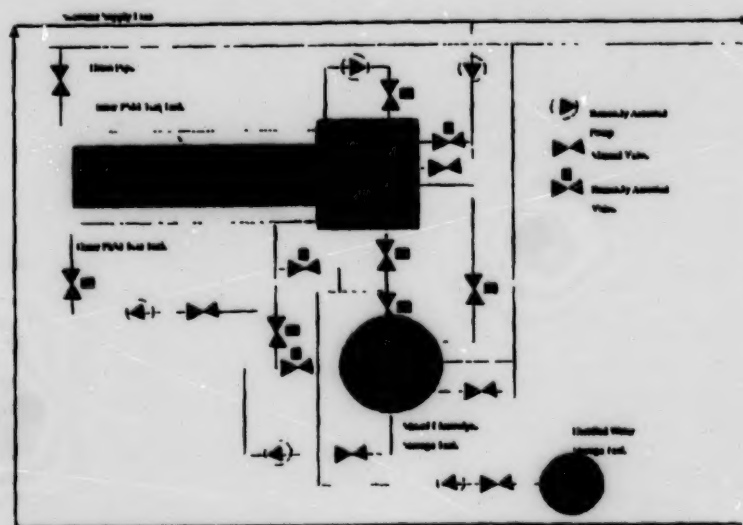


Figure 2.1 - Schematic representation of PSM facility configuration used in the ICCP modelling trials

2.2 Development of the System Hardware and Communication Protocol

2.2.1 Discussion of Analog and Digital Communication Protocols

In the "as new" state, the data acquisition system was configured as shown schematically in Figure 2.2. The system generated analog command signals to ten remotely actuated proportional valves and five on/off controlled pumps). The system acquired analog feedback signals from two flow meters in the internal and external tank recirculation loops, three conductivity meters (one each in the internal and external PSM tanks and one in the external reserve holding tank), and five pressure sensors located in various feed lines and holding tanks. Analog command and feedback signals were routed back to the control microprocessor via signal conditioners through 50 ft long individual strands of 16 gauge stranded wire contained within a metal conduit. Initial trialing of the system in its "as new" state indicated that the long runs of wire routing the analog signals back to the microprocessor were creating significant RF noise problems in both the command and feedback signals.

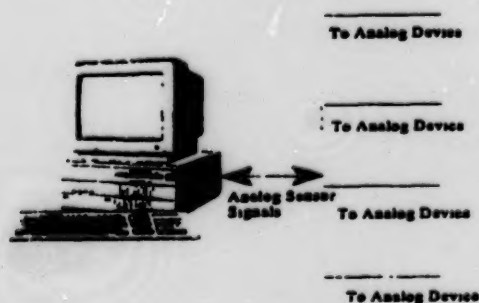


Figure 2.2 - Previous analog instrumented data acquisition system

It was proposed that much of the RF noise problem could be mitigated by close coupling the analog portions of the control and feedback circuits to the ICCP/PSM tank. Routing the control and feedback data between the close coupled analog section and the remotely located PC 586 microprocessor could be achieved by bussing the information in either a serial or a parallel digital communication protocol.

The serial communication protocol considered (Figure 2.3) busses the command/feedback data via one of the asynchronous communication ports included as standard hardware in desk top PC's. A two or three wire multi-drop RS-485 or RS-422 communications protocol would be established with the PC as the master controller and several board level slave micro controllers. Each of these micro controllers would have differing control and acquisition functions preprogrammed into RAM or an EPROM as required by the system. Preliminary trials conducted with a New Micros SPL 102 microprocessor board based on a Motorola 68HC11 chip design indicated that from a communications perspective, this system is simple and can be industrially hardened to perform the tasks required. One of the drawbacks with using this system from an ongoing system maintenance perspective is that because of the unique software preprogrammed into each microprocessor, copies of assembler routines for each micro controller would have to be maintained in the event of a micro controller crash or a power/backup battery failure.

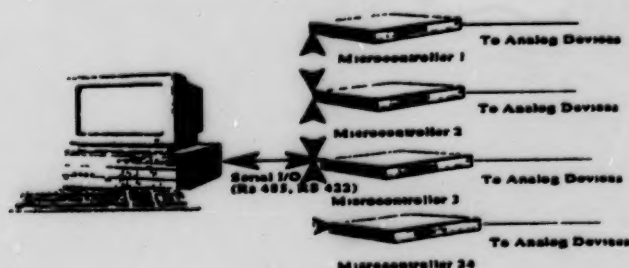


Figure 2.3 - Schematic representation of serial communication protocol

A schematic of a suitable parallel communications protocol is given in Figure 2.4. A PC based digital I/O card is used to establish one or several TTL communications busses to digital devices (ie A/D's, D/A's and multiplexers) which generate and receive the analog signals required by the ICCP/PSM facility. While this communications protocol requires increased wiring between the PC based master controller and the digital devices, it provides the end user with an increased amount of flexibility to configure the system to meet the end requirements. Also, from a software perspective, a single PC based program can be used to acquire data and control the system. For the ICCP/PSM system, it was determined that the benefits gained by using a parallel (as opposed to a serial) based communication protocol outweigh the requirements for the extra wiring required. The next several sections provide a description of the digital protocol and devices developed for controlling and acquiring data from the ICCP/PSM system.

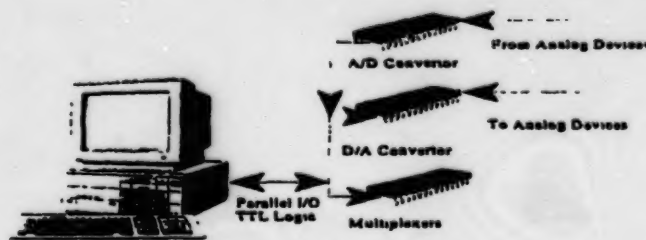


Figure 2.4 - Schematic representation of parallel communication protocol

2.2.2 PC Based Digital TTL I/O Card Selection

Two 20 line parallel busses were designed and developed to control and acquire data from the various analog sensors and controllers which comprise the PSM/ICCP facility. Providing the TTL logic levels to the individual lines was accomplished by utilizing a commercially available, PC based digital I/O card. The card selected provided a total of 120 TTL signals to control individual lines of the parallel busses. The card contains five separately addressable channels each subdivided into three 8-bit ports. Ports can be individually configured for either input or output. For the current application, channel 0 (port address 300H) was generally used as a 16-bit data bus and channel 1 (port address 304) was connected to the multiplexer bus and the pump on/off signal conditioner switches.

2.2.3 Configuration of the 16 Bit Input/Output Data Bus

The 16 bit input/output data bus is one of three digital interfaces developed to control and acquire data from the ICCP/PSM facility. The configuration of the input/output data bus is shown pictorially as bus C in Figure 2.5 and schematically in Figure 2.6. Tables 2.1 and 2.2 provide a listing of the port addresses, terminal connections, PSM bus terminal connections, wire color code connections and bit functions for this bus.

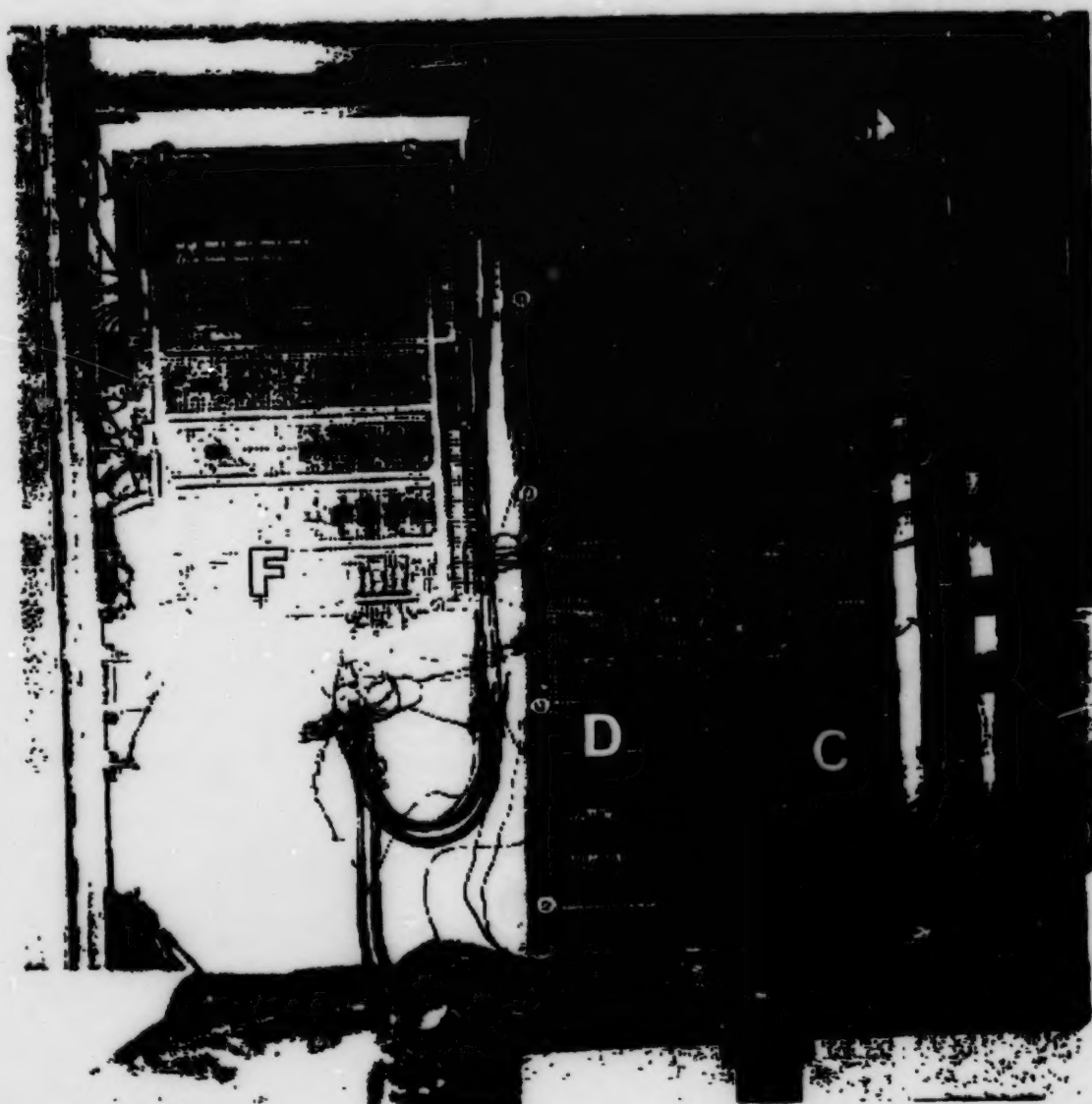


Figure 2.5 - Photograph of digital devices developed to control and acquire data from the PSM/ICCP facility.

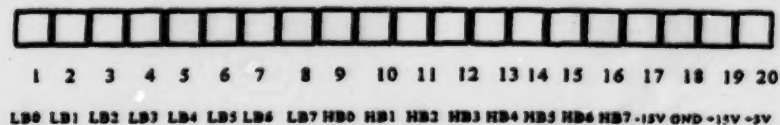


Figure 2.6 - Terminal assignment of 16-bit input/output data bus (bus C).

Table 2.1 - Channel 0 (Port 300H)

Port Address 300H	Byte No	B7	B6	B5	B4	B3	B2	B1	B0
	Computer Terminal Block No	T1-33	T1-35	T1-37	T1-39	T1-41	T1-43	T1-45	T1-47
	Wiring Code(25)**	G-R	R-G	BR-R	R-BR	Y-R	R-Y	BL-B	B-BL
	ICCP/PSM Bus Terminal No	C7	C6	C5	C4	C3	C2	C1	C0
	Digital Device Function	LB7	LB6	LB5	LB4	LB3	LB2	LB1	LB0

Note: Wire color code - First color represents the wire connected. First and second define the color combination in the twisted pair

** Note: The 25 strand shielded communication wire is received in separately shielded twisted pairs.

Table 2.2 - Channel 0 (Port 301H)

Port Address 301H	Byte No	B7	B6	B5	B4	B3	B2	B1	B0
	Computer Terminal Block No	T1-17	T1-19	T1-21	T1-23	T1-25	T1-27	T1-29	T1-31
	Wiring Code(25)**	R-B	B-R	BL-BR	BR-BL	BL-Y	Y-BL	BL-G	G-BL
	ICCP/PSM Bus Terminal No	C15	C14	C13	C12	C11	C10	C9	C8
	Digital Device Function	HB7	HB6	HB5	HB4	HB3	HB2	HB1	HB0

Note: Wire color code - First color represents the wire connected. First and second define the color combination in the twisted pair

** Note: The 25 strand shielded communication wire is received in separately shielded twisted pairs.

Two types of digital devices are controlled by the 16-bit data bus; the D/A and A/D converters. Each device is individually socketed on the bus plane for maintenance and to provide flexibility in configuring the system. For the current application, the configuration is comprised of eleven D/A converters and one A/D converter. The D/A converters are used to provide the analog signals required to position the seawater valves and to provide the command signal to the two zone ICCP hardware. The A/D converter is used to digitize the various analog sensor signals. The next two sections details the design of these two devices.

2.2.3.1 Digital to Analog (D/A) Converter Design

Figure 2.7 is a schematic representation of the D/A converters designed and fabricated for this study. The main components of the circuit are a 28-pin D/A converter IC and a high output current buffer IC. The D/A converter IC is capable of providing a $\pm 10\text{VDC}$ signal with 16 bits of resolution. The main function of the voltage follower buffer chip is to provide a high impedance block between the valve circuits and the sensitive D/A IC, as well as to boost the D/A output current capability. The buffer IC chosen is capable of delivering up to 250 mA of $\pm 10\text{VDC}$ signal to the valve drivers.

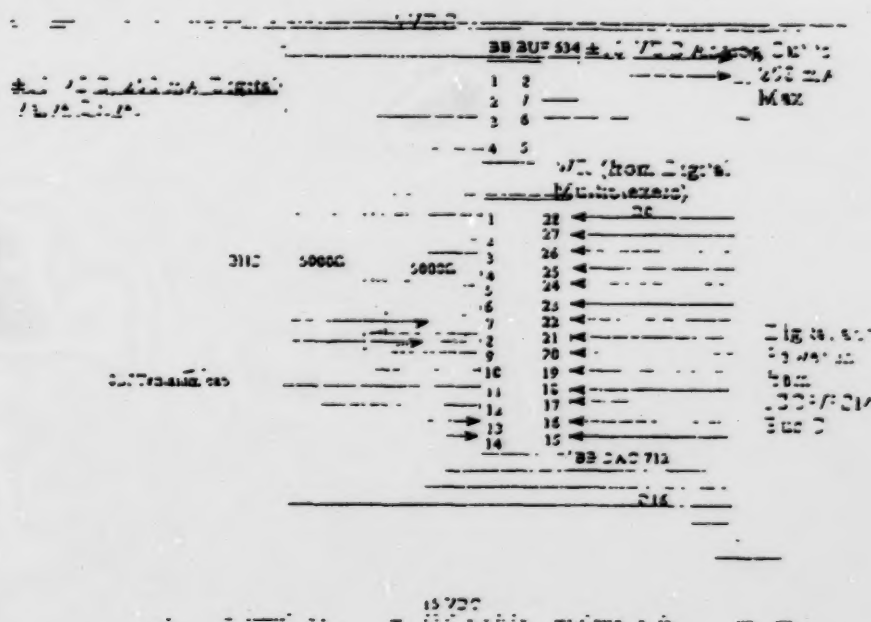


Figure 2.7 - Digital to analog convertor design

2.2.3.2 Analog to Digital (A/D) Circuit Design

Figure 2.8 is a schematic representation of the A/D converters designed and fabricated for this study. The main component of the circuit is a 28-pin A/D converter IC. The A/D converter IC is capable of digitizing a $\pm 10\text{VDC}$ signal with 16 bits of resolution.

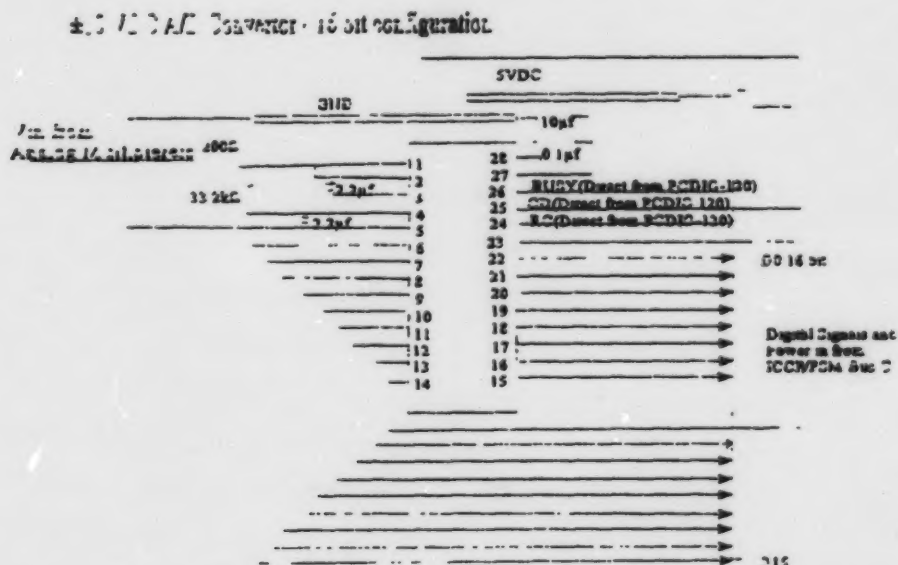


Figure 2.8 - Analog to digital convertor design

2.2.4 Configuration of the Multiplexer Control Bus

The configuration multiplexer bus is shown pictorially as bus D in Figure 2.5 and schematically in Figure 2.9. Table 2.3 provides a listing of the port addresses, terminal connections, PSM bus terminal connections, wire colour code connections and bit functions for this bus.



Figure 2.9 - Terminal assignment of multiplexer control bus (bus D).

Table 2.3 - Channel 1 (Port 304H)

Port Address 304H	Byte No	B7	B6	B5	B4	B3	B2	B1	B0
	Computer Terminal Block No	T2-33	T2-35	T2-37	T2-39	T2-41	T2-43	T2-45	T2-47
	Wiring Code (8)*	W-BL	BL-W	R-BL	BL-R	B-BL	BL-B	G-BL	BL-G
	ICCP/PSM Bus Terminal No	D13	D14	D15	D16	D17	D18	D19	D20
	Digital Device Function	EN1	EN2	EN3	EN4	EN5	A2	A1	A0

Note: Wire color code - First color represents the wire connected. First and second define the color combination in the twisted pair

** Note: The 8 strand shielded communication wire is received in separately shielded twisted pairs.

Two types of digital multiplexing devices are controlled by the multiplexing control bus; multiplexers used to provide the digital TTL logic signals to enable the D/A conversion and multiplexers used to route the various analog sensor signals to the A/D convertor. Similar to the 16-bit data bus, each device is individually socketed on the bus plane for maintenance and to provide flexibility in configuring the system. For the current application, the configuration is comprised of two digital logic multiplexers (16 logic line capacity) and three analog signal routing multiplexers (24 sensor capacity). The next two sections details the design of these two devices.

2.2.4.1 TTL Logic Generating Multiplexers

Figure 2.10 is a schematic representation of the TTL logic generating multiplexers. The main component of the circuit are two 16-pin IC multiplexers. Each multiplexer is capable of generating and routing up to eight digital logic low signals to the D/A converters. When the multiplexer is disabled, the simple resistive circuit also shown in the schematic brings all the multiplexer lines to a logic level high which holds the last D/A conversion until a logic low level is again pulsed onto that specific D/A's multiplexer line.

2.2.4.2 Analog Sensor Routing Multiplexers

Figure 2.11 is a schematic representation of the analog sensor routing multiplexers. The main component of the circuit are three 16-pin IC multiplexers. Each of the three multiplexers is capable of routing up to eight analog sensor signals to the A/D convertor.

Figure 5-2. Map size:
Scale = 1/A. Conversion:

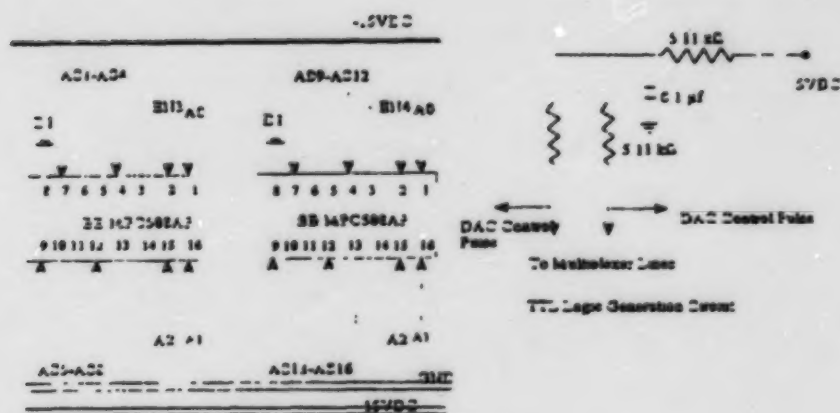


Figure 2.10 - Digital multiplexer control circuit.

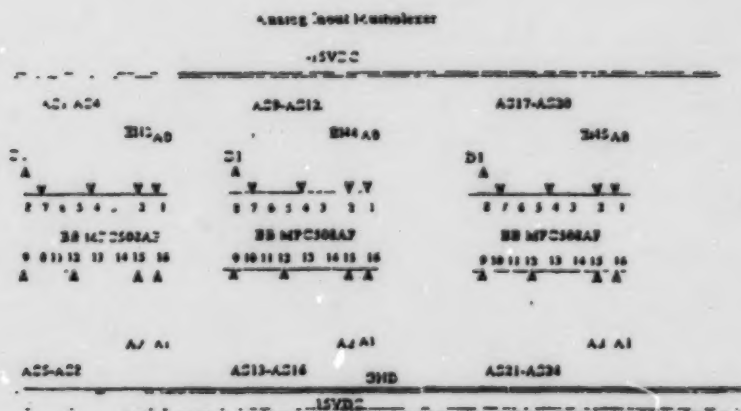


Figure 2.11 - Analog sensor signal multiplexer control circuit

2.2.5 Configuration of the Seawater Pump On/Off Control Bus

The final bus required to control the ICCP/PSM facility is the pump on/off switch bus. This bus is located remote from the PSM tank adjacent to the microprocessor. This bus provides TTL logic signals to a series of low current level relays which are used to drive a series of high power solid state relays which controls the on/off function of the pumps. Table 2.4 provides a listing of the port addresses, terminal connections, PSM bus terminal connections, wire colour code connections, and bit functions for this bus.

Table 2.4 - Channel 1 (Port 306H)

Port Address 306H	Byte No	B7	B6	B5	B4	B3	B2	B1	B0
	Terminal Block No	N/C	N/C	T2-5	T2-7	T2-9	T2-11	T2-13	N/C
	Wiring Code*(8)			R	G-BL	BL-G	B-BL	BL-B	
	ICCP/PSM Bus Terminal No			E5	E4	E3	E2	E1	
	Digital Device Function			P5	P4	P3	P2	P1	

Note: Wire color code - First color represents the wire connected. First and second define the color combination in the twisted pair.

** Note: The 8 strand shielded communication wire is received in separately shielded twisted pairs

2.2.6 Hardware Configuration of Two Zone ICCP System

The configuration ICCP control and signal conditioning circuit is shown pictorially as circuit board F in Figure 2.5 and schematically in Figure 2.12. The purpose of this hardware is to control the applied potential to the impressed current anodes and to condition the signals generated by the reference electrodes positioned along the longitudinal axis of the physical scale model. The anode command signal for each zone is independently provided by two of the 16 bit D/A convertors located on the 16 bit data bus (bus C). IR losses along the hardware circuit and electrolyte are compensated for by comparing the command signal to the feedback signal from the control reference electrode in a PID control circuit. A measure of anode current for each zone is generated by inserting a resistance in series with the auxiliary electrode (anode). The voltage drop generated across this resistor is routed to the A/D convertor via the analog multiplexers. Reference electrode potentials from the physical scale model are also routed to the A/D convertor in a similar manner.

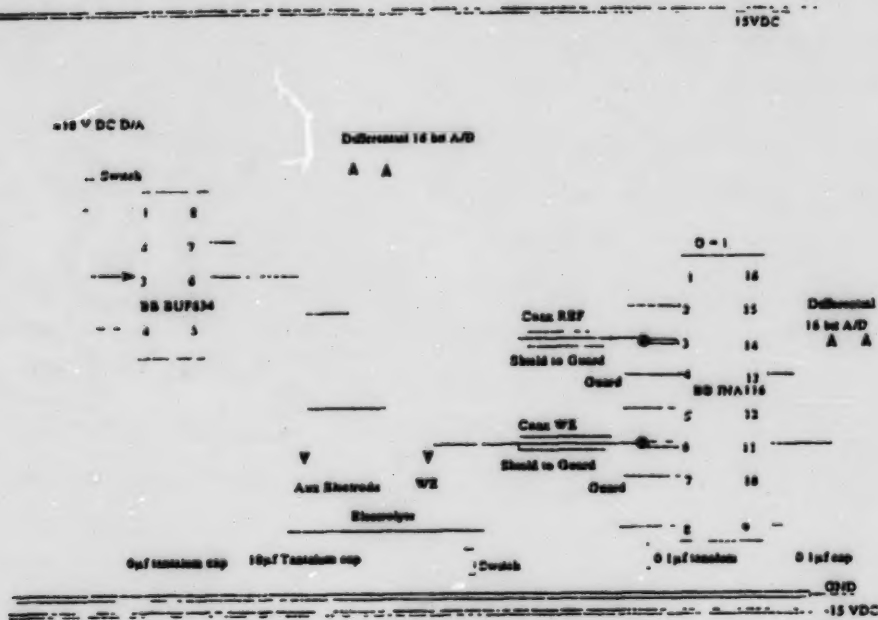


Figure 2.12 - Schematic representation of the circuit which controls one zone of the two zone ICCP system for the physical scale model. The control circuit for the second zone is functionally similar to the schematic above.

2.3 Software Development for the PSM/ICCP Facility

The DREA ICCP/PSM instrumented control and acquisition system is an R&D oriented software package designed for controlling the PSM/ICCP test facility and gathering and analysing data generated by the sensor suite configured into the system. Once the system has been configured, data base generation and maintenance is self supervising. Using this system requires no previous experience with computers. The system has a single control display which allows the operator complete access to the program functions. To initiate the program and generate the control display, choose the ICCP icon from the Windows program menu.

The software package consists of a single executable "ICCP.EXE" and a single dynamic link library "CW3215.DLL" which combine to generate a custom designed virtual instrument which executes the data acquisition and control sequences. The system was designed for Windows 95/98, a 32 bit environment and will not execute properly in 16 bit environments such as DOS or Windows 3.1.

The programming language used to program the ICCP/PSM system was C++ using a Borland 32 bit compiler to assemble the C++ code into machine code. To circumvent the timing issues which are normally associated with real time programming under Windows 95/98 operating platforms, I/O sections were programmed in 8086 assembler language for direct register access of the I/O ports provided by the digital interface communications card.

A bit map of the user interface associated with this program is shown in Figure 2.13. The display is divided into three sections. The column of scroll box and radio button windows located on the left hand side of the display are for manually controlling the position of the seawater valves and the on/off status of the seawater pumps. These windows can also be used to configure the same devices for automated control. The upper right hand section of the screen is used to configure the PSM command set points as well as tracking the status of the feedback signals obtained from the PSM sensors (ie conductivity, seawater temperature, etc). The track bars at the far right of this section can be used to set the appropriate upper and lower control limits for the variable of interest.

The bottom section of the main display is used to configure the command signals to the two zone ICCP hardware and to track the feedback signals from the controlling reference electrodes. Any of the 10 reference electrodes configured into the longitudinal axis of the model can be hardware configured to provide the feedback control signal.

The popdown menus accessed through the main menu (located at the top of the screen provide several functions. These functions include:

- Inputting calibration data for the PSM sensors

- Configuring the ICCP experiment event sequencing
- Providing a graphical display of the hull potential profiles generated by the reference electrodes.

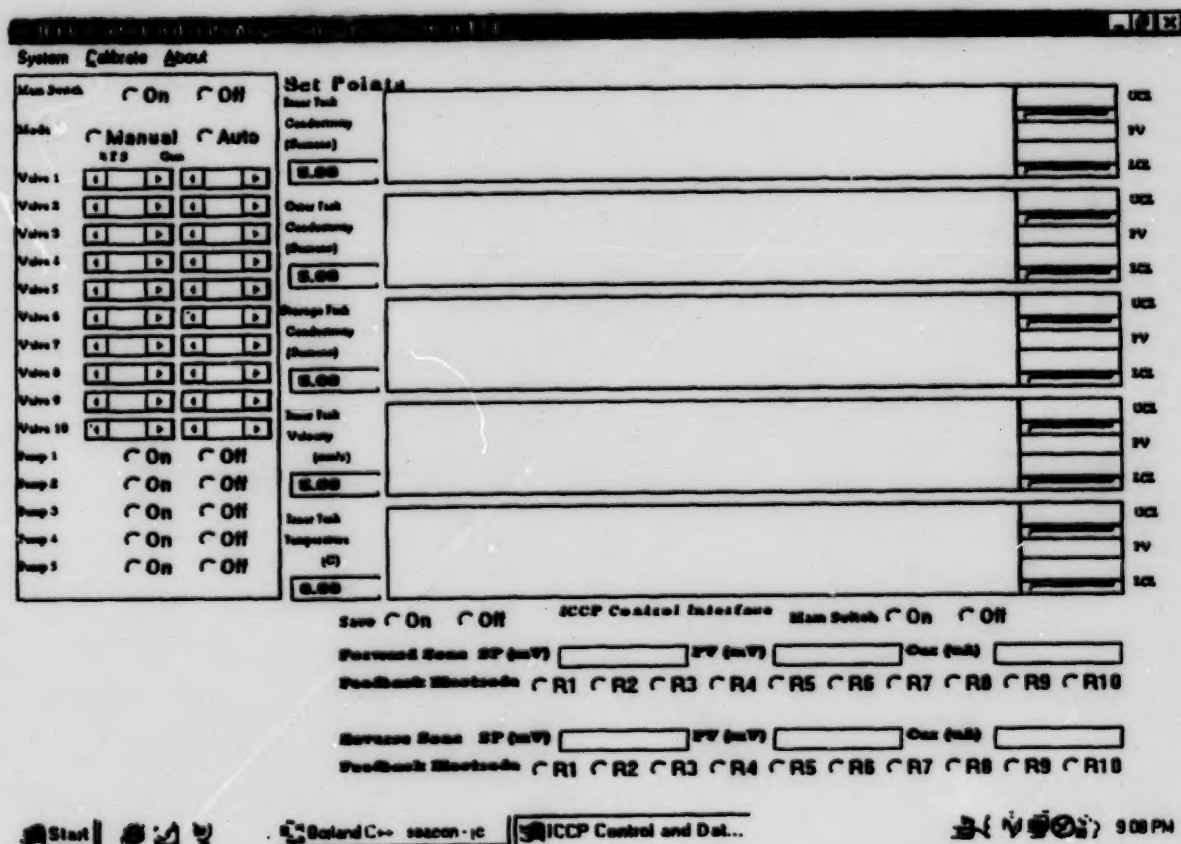


Figure 2.13 - GUI for DREA ICCP instrumented control and acquisition system.

3.0 PHYSICAL SCALE MODEL DEVELOPMENT

3.1 Fabrication of the PSM Model

The 1/100 scale male PSM was produced using facilities at the NSCAD/CAM center in Halifax. The hull shape was obtained from DREA (Hydrodynamics group) as a series of hull offsets. The hull offsets were supplied to the NSCAD/CAM center who generated a 3D surface of the hull from the 7m elevation down to the keel line. Based on the 3D surface tool paths were generated for the machining operations using SmartCAM 3-axis machining software.

The male PSM was machined from a block of high density styrofoamSM. The block was fabricated by glueing three layers of 50mm thick sheets together using epoxy. The layers were held in a press after glueing to ensure a thin and even glue line.

The initial machining removed the bulk of the material surrounding the hull using a 0.5 inch flat end mill. A 1 inch vertical relief was machined past the 7 meter elevation to provide clearance for the bit during final machining. Final machining consisted of passes in the transverse direction with a 1 inch ball end mill advancing forward 0.010 inch after each pass.

The length of the PSM exceeded the length of the machine bed and therefore the machining was performed in 3 segments. The aft section was machined first and then the material was moved rearward on the machine bed so the midsection, and then the forward section could be machined. Two alignment holes were made in the base of the PSM to guarantee accurate placement after each move. Figure 3.1 is a photograph of PSM insert after machining was completed.

The machined PSM was coated with fibreglass/epoxy resin to provide additional strength and hardness. Brian Liekens, a local model boat builder, was subcontracted to perform this work. Locations where tear-out had occurred during machining were filled (these were mostly near the stern where the glue joint made a shallow angle to the surface) and then a coating of epoxy resin was applied and allowed to harden. A layer of fibreglass modelling cloth was then applied to the PSM with epoxy resin. An additional coating of epoxy was applied to the hull and the surface was lightly sanded to provide a smooth surface (Figure 3.2).

A female mould was fabricated from the male mould by suspending the male mould (plug) in a prefabricated casting box. To ensure a complete release of the plug after the casting, the surface of the male plug was coated with a thin coating of petroleum jelly. The box with the male mould suspended in it was then filled to the top level of the plug using a casting mortar and left to cure for 24 hours. The male plug was subsequently removed from the casting after curing and any imperfections observed in the hull form surface were refilled and allowed to cure. Once the surface of the hull form was satisfactory, four coatings of poly urethane were applied to the mould followed by two coats of mould release.

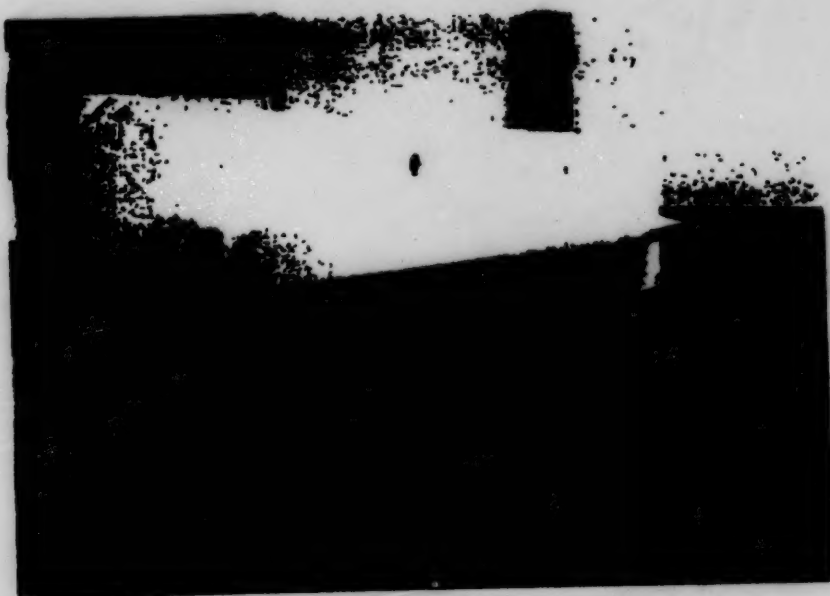


Figure 3.1 Styrofoam insert prior to being coated with fiberglass



Figure 3.2 Styrofoam insert after being coated with fiberglass

The physical scale model was fabricated using the female mould. To provide the through hull penetrations required to instrument the model with reference electrodes and anodes, a lattice structure which was laid on top of the mould and referenced to the bow of the model was constructed. A polished steel rod ($\frac{1}{2}$ inch in diameter) was inserted through holes machined into this lattice where a hull penetration was required (see Figure 3.3 and Figure 3.4 for position of through hull penetrations). Prior to inserting the rod, they were coated with two coats of mould release. The model was cast in $\frac{1}{2}$ inch layers to minimize cracking using a cold cure epoxy. Once the model was fully cast, it was allowed to cure for 24 hours prior to removal from the mould. The through hull penetrations were subsequently machined to remove any spurs formed during the casting process. Imperfections observed on the hull surface were filled with an epoxy filler. The entire hull surface was lightly sanded and the model was coated with two coats of epoxy paint.

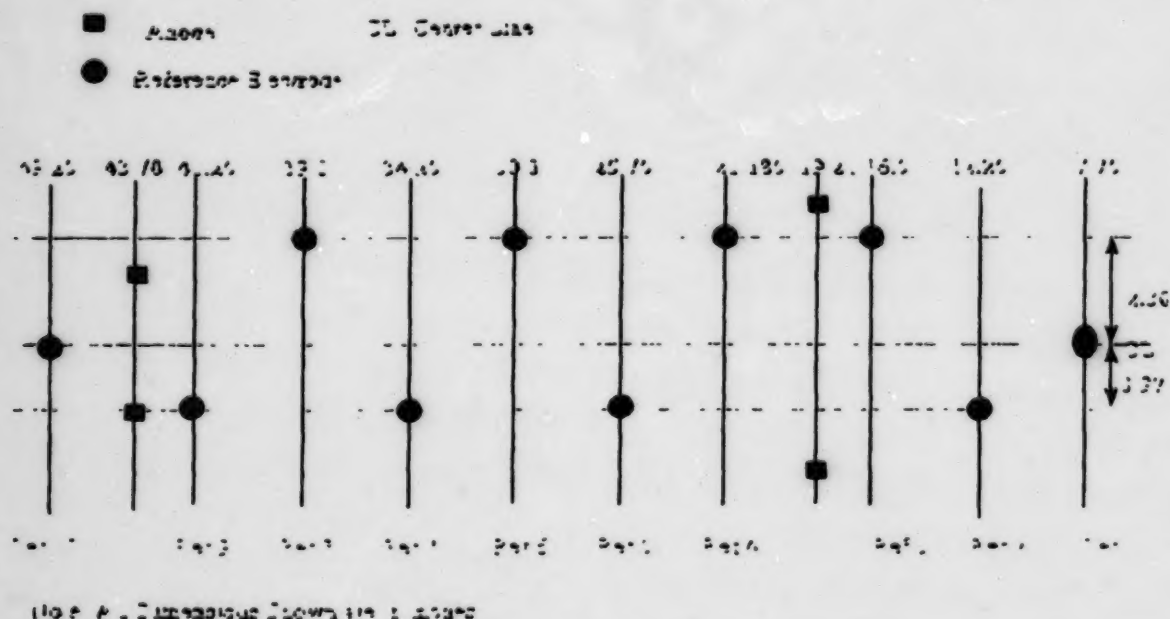


Figure 3.3 - Anode and reference electrode sensor positions for the PSM model constructed

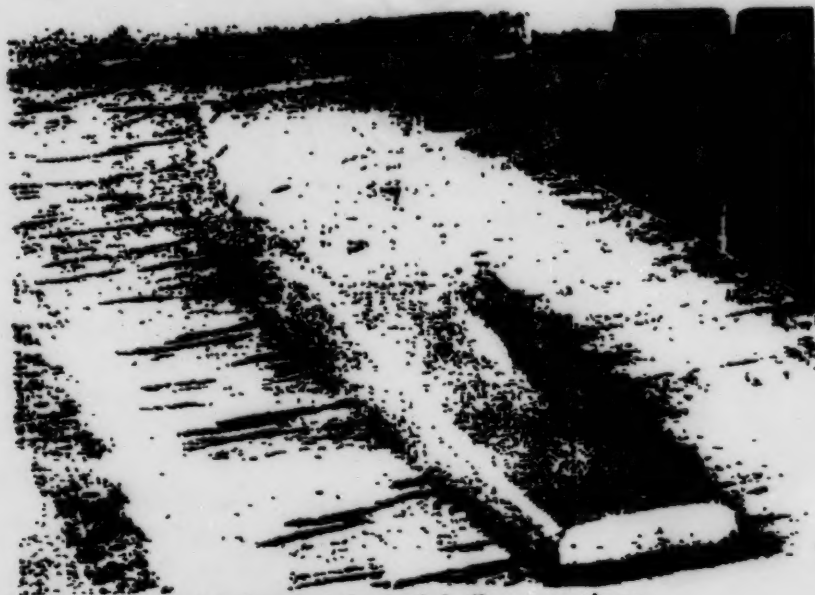


Figure 3.4 - Physical scale model showing through hull penetrations.

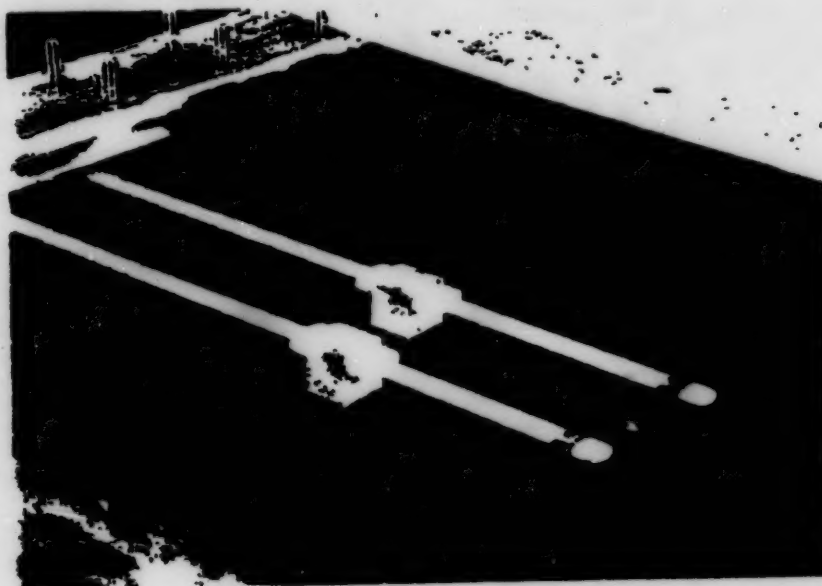


Figure 3.5 Physical scale model of dual propellers are simulated using flat NAB disks

Two nickel aluminum disks 44 mm in diameter and 3 mm in thickness were machined to simulate the propeller area (Figure 3.5). The disks were attached to a constant speed AC motor via an epoxy coated steel shaft and ratio pulleys to provide the desired rotational velocity to the disks. Controlling the rotational velocity of the disks was achieved by varying the ratio of the drive pulleys. The disk shafts penetrated the rear wall of the PSM/ICCP inner tank (as opposed to penetrating the model) owing to the relatively constructional simplicity afforded by this approach.

3.2 Instrumentation of Physical Scale Model

In order to carry out experiments which characterize impressed current cathodic protection systems, the model must contain two main components, namely impressed current anodes and reference electrodes to control/monitor the performance of the system. For the current model fabricated, four high density graphite anodes were installed in the system in order to simulate the CPF operational configuration. Two anodes are located in the aft zone fore of the propellers and two in the forward zone. CPF has only three reference electrodes, one aft of the propellers, one in mid section of the ship and one on the fore of the hull. Because of the increased detail required to compare the PSM results to the computational results, ten gel filled Ag/AgCl reference electrodes were positioned along the longitudinal axis of the PSM hull form (see Figure 3.3 and 3.4).

4.0 EXPERIMENTAL PROGRAM

4.1 Procedure for Generating Potentiodynamic Polarization Resistance Data

The computational modelling required polarization resistance information as one of several inputs to generate hull potential profiles for comparison with the PSM trials. Initial PSM trials used an epoxy hull form combined with nickel-aluminum bronze (NAB) propellers. Thus for these comparison trials, only NAB polarization resistance data was required as input data to the computational model. Prior to testing the NAB specimens, verification of the system calibration was conducted with 430 stainless steel calibration specimens in accordance with the potentiodynamic test procedure as outlined in ASTM G5. Once system calibration was verified, the following laboratory procedure and methodology was used to obtain the NAB polarization resistance data.

4.1.1 Specimen Preparation

- a) Specimens were machined from the supplied NAB material to the following dimensions; diameter- 9.50mm, height-12.70mm. Dielectric epoxy was applied to the bottom of the specimens used for the rotating tests to prevent exposure of this surface to the test solution.
- b) Wet grind and polish all exposed surfaces of sample to 600 grit using progressively finer SiC papers (240, 320, 600 grits).
- c) Determine exposed surface area of sample by measuring sample dimensions to nearest 0.01mm. For static tests calculate the area of the top, cylindrical side and bottom and subtract the area under the Teflon compression gasket. For the rotating tests, only the sides of the cylinder are exposed.
- d) Ultrasonically clean the specimen in an acetone bath for 5 minutes.

4.1.2 Test Solution

- a) For the NAB specimens, the test solution consists of the appropriate ratio of sea water and distilled water. Once prepared, 900ml of the solution is transferred to the cleaned test cell. This test cell is then placed in a water bath kept at a constant temperature of 21°C. Purge the solution for ½ hour prior to the immersion of the test sample with air at a rate of 200cm³/min. This air purge is maintained for the duration of the test.

4.1.3 Procedure

- a) The specimen is attached to the specimen holder while suitable precautions are taken to maintain proper surface condition (ie. Teflon tongs, surgical gloves, etc.). The specimen holder for the static test is a standard apparatus as outlined in ASTM-G5 (Figure 4.1). The test cell, also outlined in G5, provides proper support for the two graphite electrodes, the sample holder, the gas purge device, and the calomel reference electrode with a salt bridge

probe For the rotating test, the specimen is mounted on the end of a stainless steel rod assembly that connects to a variable speed motor (Figure 4.2). This rod assembly is constructed so as to electrically isolate the sample from the motor. A Teflon cylinder mates against the top of the test sample to prevent exposure of this surface to the test solution. In both test setups, the graphite rods are located on opposite sides of the specimen and the salt bridge probe tip is positioned approximately 2mm from the specimen

c) Once the specimen is immersed, the open circuit potential of the specimen is monitored for 60 minutes. After 55 minutes, the open circuit potential is recorded.

d) After the 60 minute immersion (for the rotating tests commence rotation of the specimen at the chosen rpm) start the potential scan 10mV from the corrosion potential measured above. A potential step rate of 10mV every minute is maintained, with the current recorded 5 seconds prior to the end of each 1 minute step period.



Figure 4.1 - Photograph of corrosion cell configuration used to generate the static polarization resistance curves.

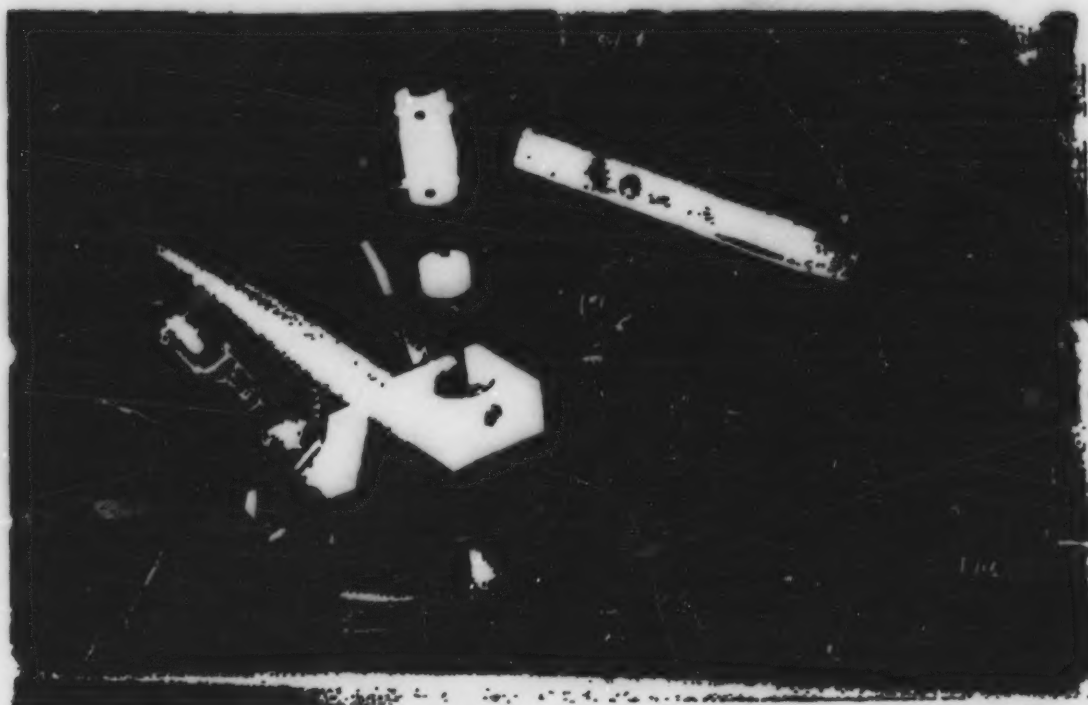


Figure 4.2 - Photograph of the corrosion cell configuration used to conduct the dynamic polarization resistance testing.

4.2 Physical Scale Modelling (PSM) Procedure

The following section details the experimental procedure conducted prior to and during the PSM trials. Prior to inserting the ten Ag/AgCl reference electrodes into the model, the accuracy of each reference electrode was verified by checking the open circuit potential against a precision grade saturated calomel electrode. Once calibration of each electrode was checked, it was inserted into the appropriate hull penetration in the epoxy model so the sensor tip was flush with the outer surface of the model. Four high density graphite impressed current anodes (two aft and two forward) were inserted in the remaining hull penetrations. Once inserted and positioned, the electrodes/anodes were sealed into the model using a silicone based sealant to minimize the egress of seawater from any incomplete fit between the model and the electrode/anodes. Prior to sealing the top of the model tank, the NAB propeller disk surfaces were polished using 600 grit emery paper. The top of the PSM tank with the model attached was then sealed and the reference electrodes and the anodes were connected to the close coupled hardware using shielded coax wire with BNC connections. To provide a check on the aft and forward currents being recorded by the microprocessor based data acquisition system, an analog current meter was placed in series between the anode and the close coupled hardware.

Prior to initiating the testing sequence, The PSM inner tank was filled with 1/100 (approx 4 mill mho/cm) scale electrolyte with naturally occurring seawater as the base. The inner tank water circulation and the aeration pumps were activated for 24 hours prior to testing to ensure oxygen saturation of the electrolyte.

Four ICCP test configurations were evaluated using the PSM facility. Table 4.1 contains the details of the reference electrode combinations used during the trials. The four combinations chosen were selected to approximate the current configurations available to CPF ICCP operators. For each configuration, three applied potentials (at the appropriate controlling reference electrode) were evaluated, namely -0.6V, -0.8V and -1.0V with respect to a Ag/AgCl reference. At each applied potential, the ten reference electrode voltages and two anode currents were recorded for subsequent analysis.

Table 4.1 - ICCP/PSM model configurations trialed.

Configuration No.	Reference Electrode Controlling Forward Anodes	Reference Electrode Controlling Aft Anodes	Propeller Velocity (RPM)
1	Ref 2	Ref 10 (aft-aft)	0
2	Ref 2	Ref 8 (mid-aft)	0
3	Ref 2	Ref 10 (aft-aft)	3450
4	Ref 2	Ref 8 (mid-aft)	3450

4.3 CPBEM CODE MODIFICATIONS

As part of the current contract, the CPBEM solver was upgraded in order to provide two new modeling capabilities: the ability to define dynamic polarization curve data and the ability to simulate interior fluid domains. Details related to the implementation of both these new capabilities are described in detail in the sections below.

4.3.1 Incorporation of Dynamic Polarization Curves

In the original version of the CPBEM solver, the polarization curve definition was very difficult to modify. In fact, modification of this data required changes to the actual source code itself. In order to avoid this time consuming and awkward approach, CPBEM was upgraded to provide users with the capability of pre-defining several different polarization curves in advance. By doing so, users can associate a particular polarization curve with a particular speed. Users can then simply assign the propeller velocity at run time, and CPBEM will determine which of the polarization curves stored in its database should be used. In the event that a polarization curve does not exist for the particular speed specified by the user, CPBEM will create a new polarization curve by interpolation between curves defined at velocities bracketing the specified velocity.

4.3.2 Incorporation of a Interior Domain Modeling Capability

In the previous version of the CPBEM solver, the structure was assumed to be immersed in an infinite fluid domain. As a result, the model boundary included not only the wet surface of the structure (S), but also a "fictitious" outer surface (S_2) representing the imaginary boundary at infinity (see Figure 4.4). The surface representing the infinite boundary was assumed to be spherical in shape and reside at a distance R from the structural boundary (where $R \rightarrow \infty$). The resulting boundary integral formulation

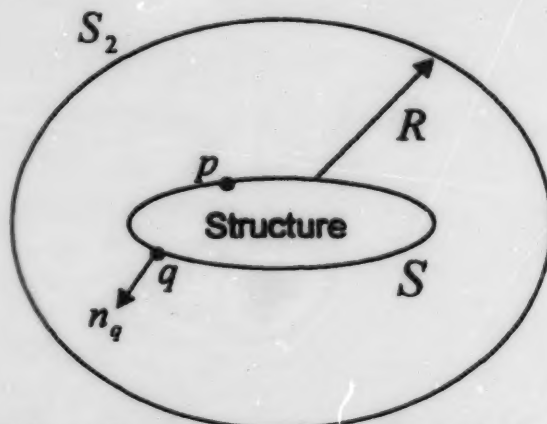


Figure 4.4: Fictitious Boundary in an Infinite Electrolyte

was expressed in the following form:

$$2\pi\phi(p) = \int_S \left[\phi(q) \frac{\partial}{\partial n_q} \left(\frac{1}{r_{pq}} \right) - \left(\frac{1}{r_{pq}} \right) \left(\frac{\partial \phi(q)}{\partial n_q} \right) \right] dS_q - \int_{S_2} \left[\phi(q) \frac{\partial}{\partial n_q} \left(\frac{1}{r_{pq}} \right) - \left(\frac{1}{r_{pq}} \right) \left(\frac{\partial \phi(q)}{\partial n_q} \right) \right] dS_q$$

where S represents the wet surface of the body, p and q represent points located on S , $\phi(p)$ represents the electrical potential at point p , n_q represents the surface normal (pointing out of the fluid) at point q , and r_{pq} represents the distance between points p and q .

Fortunately, by applying the infinite boundary conditions, i.e.: $\phi = O(1/R^2) + \phi_\infty$ (as R approaches ∞), the integral equation provided above reduces to the following form [9]:

$$2\pi\phi(p) = \int_S \left[\phi(q) \frac{\partial}{\partial n_q} \left(\frac{1}{r_{pq}} \right) - \left(\frac{1}{r_{pq}} \right) \left(\frac{\partial \phi(q)}{\partial n_q} \right) \right] dS_q + 4\pi\phi_\infty \quad (4.2)$$

The CPBEM procedure used for solving Equation (4.2) followed a conventional boundary element technique. First, the wet surface of the structure is discretized into a series of " N " small panels (originally triangular panels). Next, the strengths of the doublets (i.e.: $\frac{\partial \phi(q)}{\partial n_q}$) and sources (i.e.: $\phi(q)$) are uniformly distributed over each panel.

This leads to a system of equations that can then be solved for the unknown potentials and fluxes, i.e.:

$$\begin{bmatrix} H_{11} & H_{12} & \dots & H_{1N} & 2C\pi \\ H_{21} & H_{22} & \dots & H_{2N} & 2C\pi \\ \dots & \dots & \dots & \dots & \dots \\ H_{N1} & H_{N2} & \dots & H_{NN} & 2C\pi \\ 0 & 0 & \dots & 0 & 0 \end{bmatrix} \begin{bmatrix} \phi_1 \\ \phi_2 \\ \dots \\ \phi_N \\ \phi_\infty \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & \dots & G_{1N} \\ G_{21} & G_{22} & \dots & G_{2N} \\ \dots & \dots & \dots & \dots \\ G_{N1} & G_{N2} & \dots & G_{NN} \\ A_1 & A_2 & \dots & A_N \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ \dots \\ q_N \end{bmatrix} \quad (4.3)$$

where ϕ_i represents the potential computed for panel " i ", q_i represents the flux computed for panel " i ", A_i represents the area of panel " i ", $C = 2$ (for 3-D problems) and H_{ij} and G_{ij} are computed using the following expressions:

$$H_{ij} = \begin{cases} C\pi, & \longrightarrow i = j \\ \int_{S_j} \frac{\partial}{\partial n_{ij}} \left(\frac{1}{r_{pq}} \right) dS_j, & \longrightarrow i \neq j \end{cases}$$

$$G_{ij} = \int_{S_j} \left(\frac{1}{r_{pq}} \right) dS_j$$

In order to extend CPBEM to provide for the modeling and analysis of interior fluid domains a number of modifications had to be made to the procedure described above. Perhaps the most fundamental of these changes involved the governing integral equation. Because the interior problem does not include the infinite boundary S_∞ , the ϕ_∞ term no longer has any physical significance and had to be removed from the interior formulation. This led to the development and implementation of a new form of the governing integral equation, i.e.:

$$2\pi\phi(p) = \int_S \left[\phi(q) \frac{\partial}{\partial n_{ij}} \left(\frac{1}{r_{pq}} \right) - \left(\frac{1}{r_{pq}} \right) \left(\frac{\partial \phi(q)}{\partial n_{ij}} \right) \right] dS_q \quad (4.4)$$

Removing the ϕ_∞ term also impacted on the format of the assembled boundary element matrix equations. This new "interior" system of equations, provided below in Equation (4.5), has a size of " $N \times N$ ", as opposed to the exterior form which included an additional row and column in order to account for the calculation of ϕ_∞ .

$$\begin{bmatrix} H_{11} & H_{12} & \dots & H_{1N} \\ H_{21} & H_{22} & \dots & H_{2N} \\ \dots & \dots & \dots & \dots \\ H_{N1} & H_{N2} & \dots & H_{NN} \end{bmatrix} \begin{Bmatrix} \phi_1 \\ \phi_2 \\ \dots \\ \phi_N \end{Bmatrix} = \begin{bmatrix} G_{11} & G_{12} & \dots & G_{1N} \\ G_{21} & G_{22} & \dots & G_{2N} \\ \dots & \dots & \dots & \dots \\ G_{N1} & G_{N2} & \dots & G_{NN} \end{bmatrix} \begin{Bmatrix} q_1 \\ q_2 \\ \dots \\ q_N \end{Bmatrix} \quad (4.5)$$

Other minor changes to the code included modifications to the I/O routines and the development of a new graphical user interface for the CPBEM solver (see Figure 4.5). This GUI allows users to select the type of analysis to be performed (i.e.: interior or exterior) and view the results in terms of panel potentials and flux (see Figure 4.6).

4.3.3 Test Cases

In order to verify the accuracy of the new interior domain modeling feature a series of three numerical trials were performed. For the purposes of this investigation a model of a circular cylinder was developed (length of 10 and a radius of 1). Figure 4.4 provides a plot the CPBEM model of this cylinder: the anode is represented by the blue panels, the cathode is represented by the green panels, and the insulation is represented by the red panels.

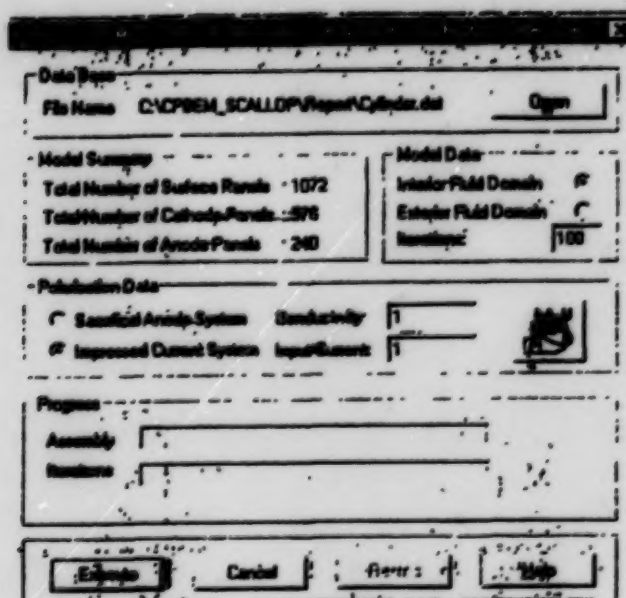


Figure 4.5: New CPBEM Solver GUI

This particular model was selected because both analytical results and numerical results from a previous investigation [9] were available. In order to compare the results to the other numerical study the same polarization curve data was used (see Figure 4.8).

The first case involved modeling the interior domain of the cylinder. The CPBEM results, provided below in Figure 4.9, compare very well to both the analytical results and previously published results (see Figure 4.10).

The second case involved modeling the fluid domain exterior to the cylinder. These results are provided below in Figure 4.11. A comparison of these results to the published values (see Figure 4.12) also appears to show very close agreement.

The third and last set of comparisons involves a model of the cylinder immersed in a finite bounding box (see Figure 4.13). In order to reduce the number of boundary element panels, only a quarter of the model was panelized. This scenario is quite similar to the experimental set described in previous sections of this report. As expected, the CPBEM results (see Figure 4.14) for this case are quite similar to the infinite field results provided in Figure 4.11. In fact, it appears that the bounding box (modeled as an insulator) has very little effect on the potential distribution on the cylinder surface.

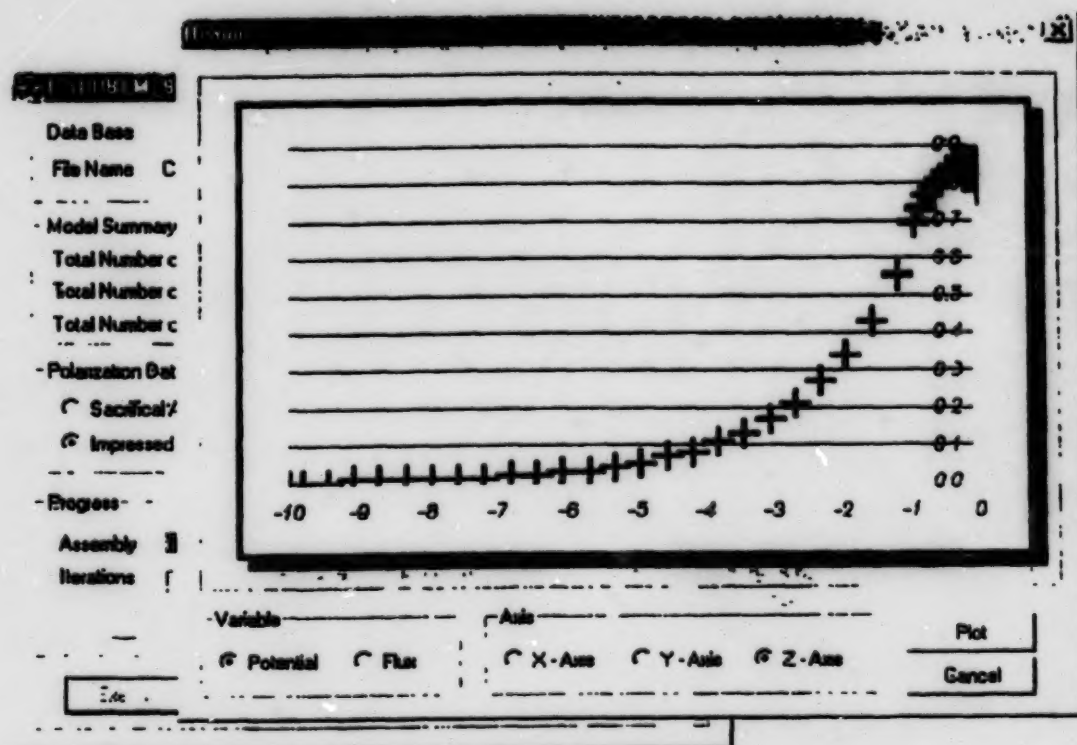


Figure 4.6: CPBEM Solver GUI Results Display



Figure 4.7: Boundary Element Model Circular Cylinder

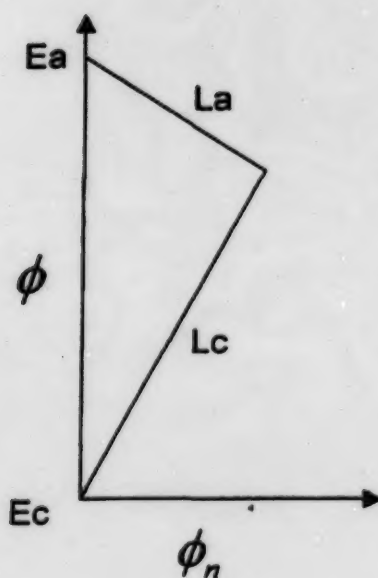


Figure 4.8. Polarization Curve Data ($E_a = 1$, $E_c = 0$, $L_a = 1$, $E_c = 5$)

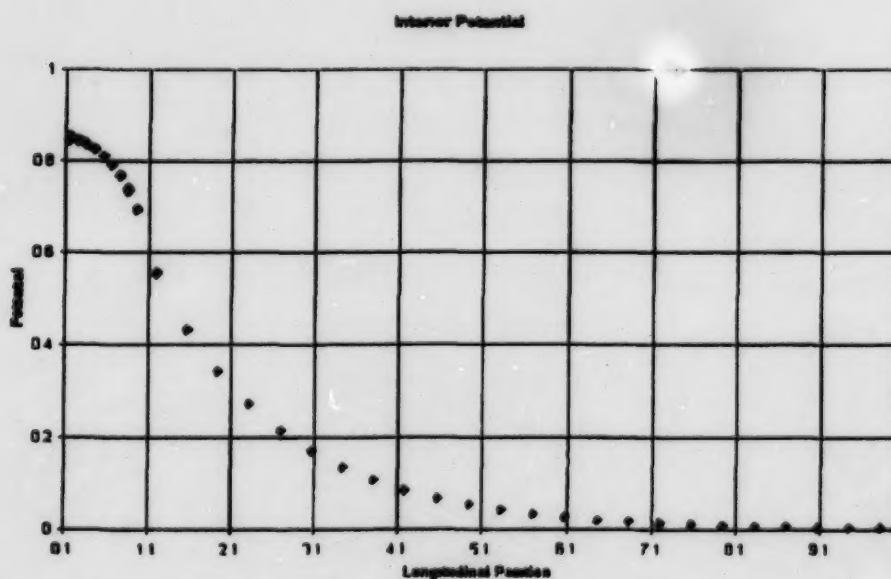


Figure 4.9a: CPBEM Interior Potential Results

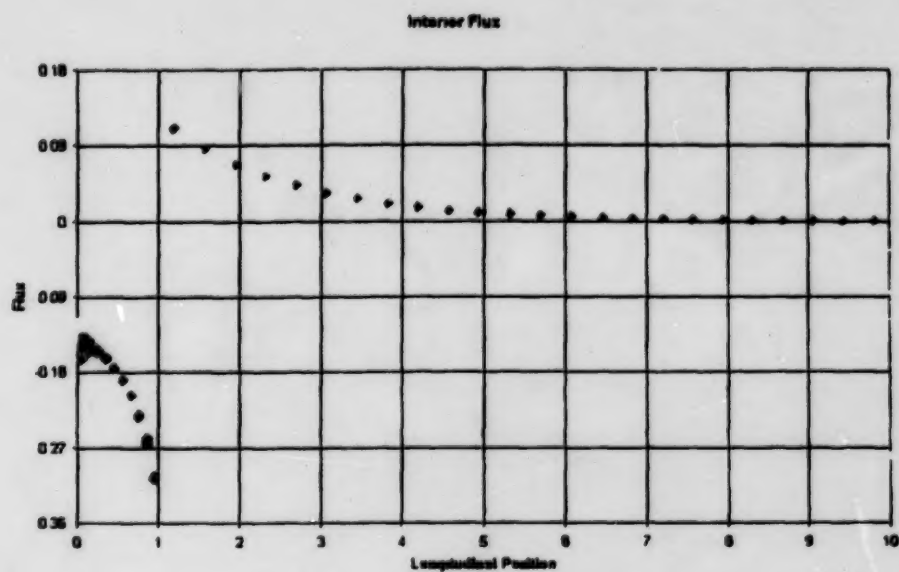


Figure 4.9b: CPBEM Interior Flux Results

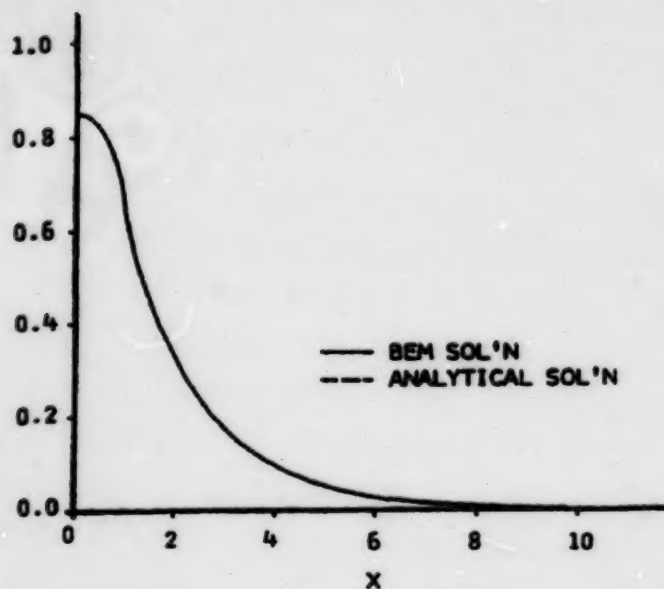


Fig. 35 Comparison between different Solutions (Potential)

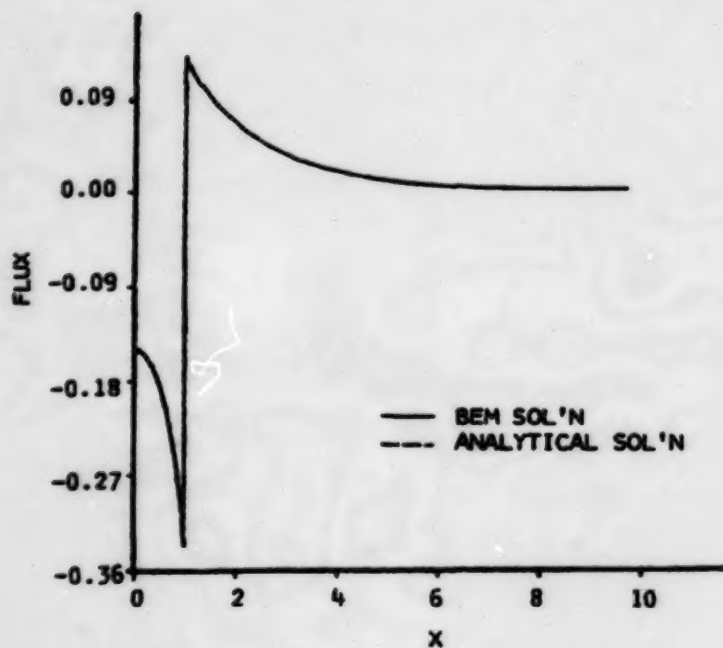


Fig. 4.10 Comparison between Different Solutions (Flux)

Figure 4.10: Analytical and Published Interior Results

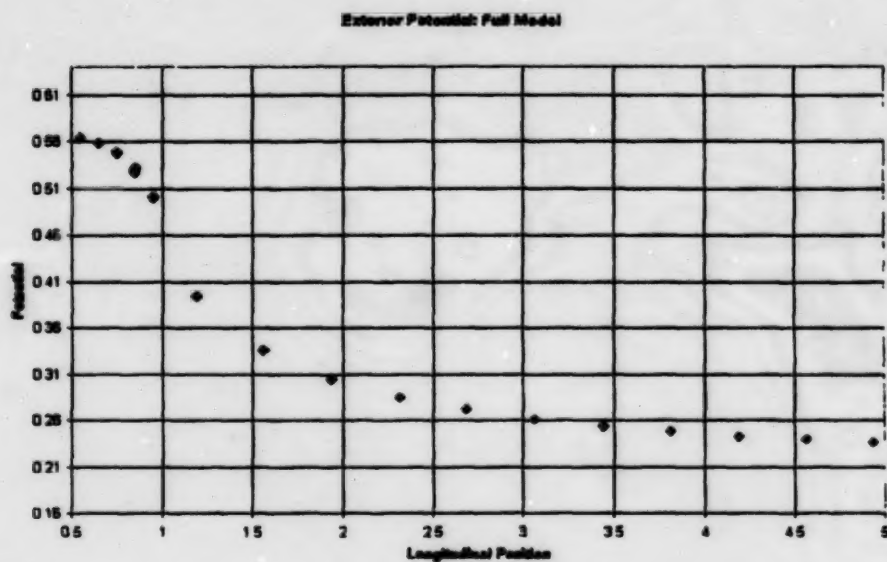


Figure 4.11a: CPBEM Exterior Potential Results

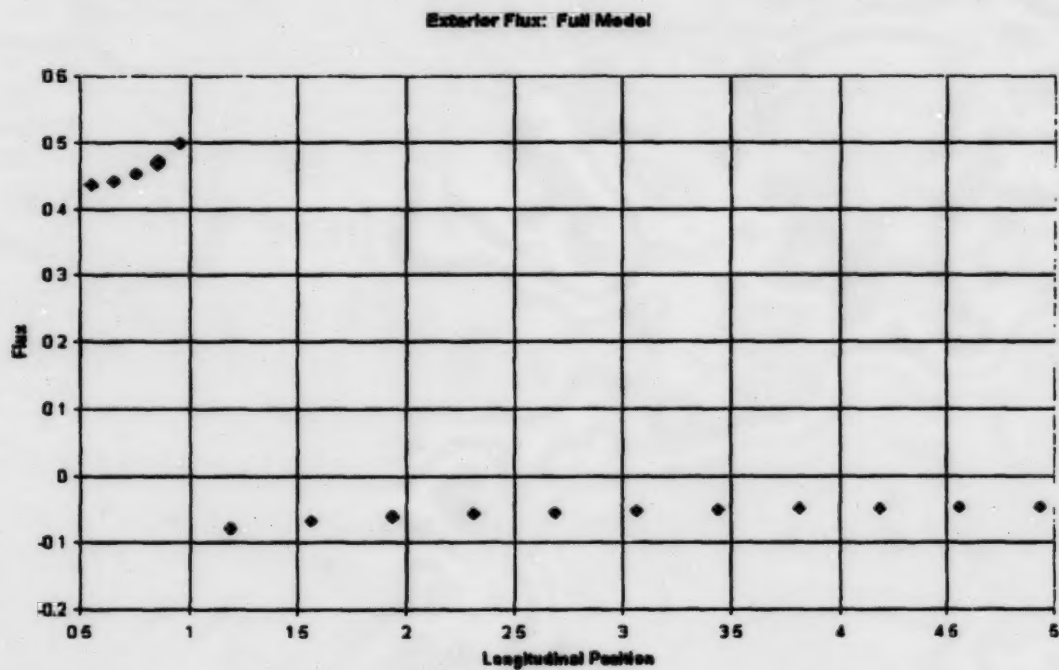


Figure 4.11b: CPBEM Exterior Flux Results

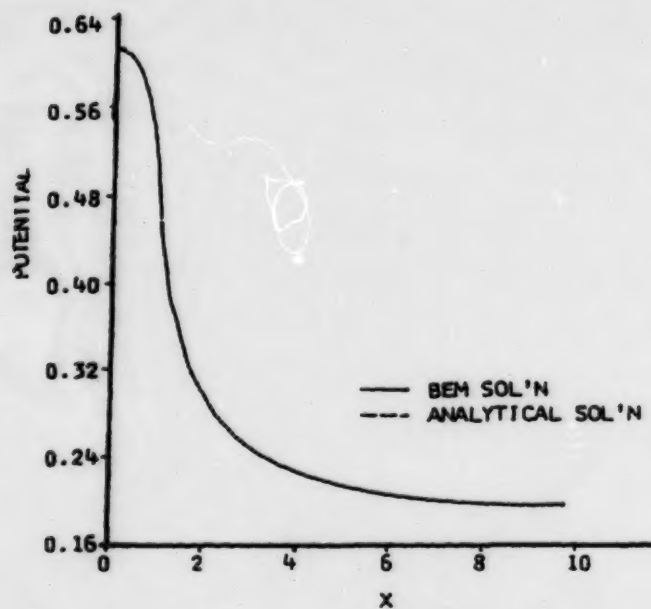


Fig. 40 Comparison between Different Solutions (Potential)

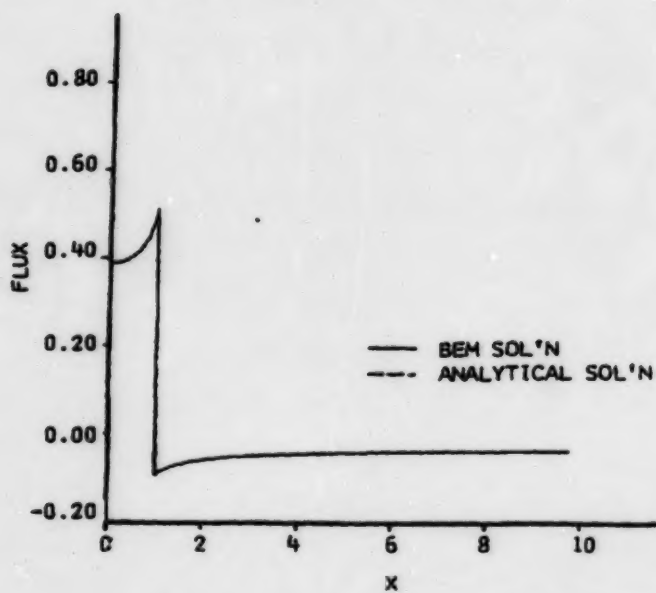


Fig. 41 comparison Between Different Solutions (Flux)

Figure 4.12: Published Exterior Potential/Flux Results

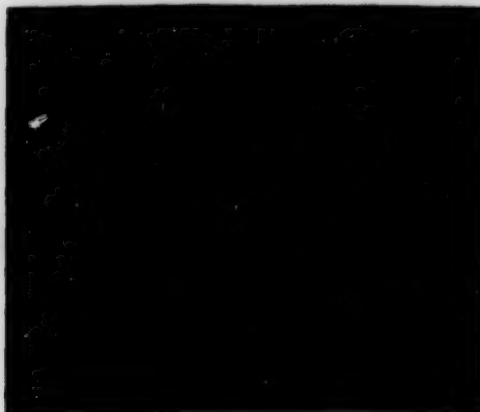


Figure 4.13a: Cylinder Immersed in Box

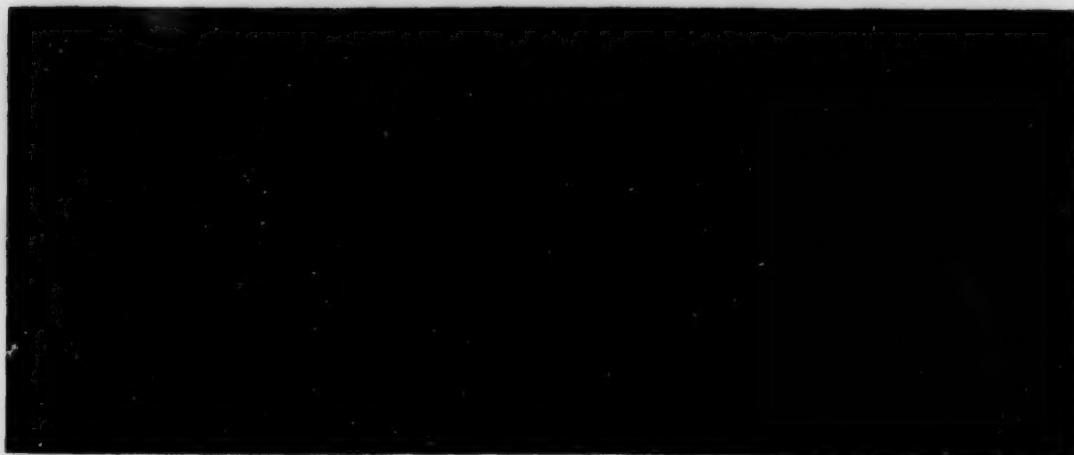


Figure 4.13b: Cylinder Immersed in Box

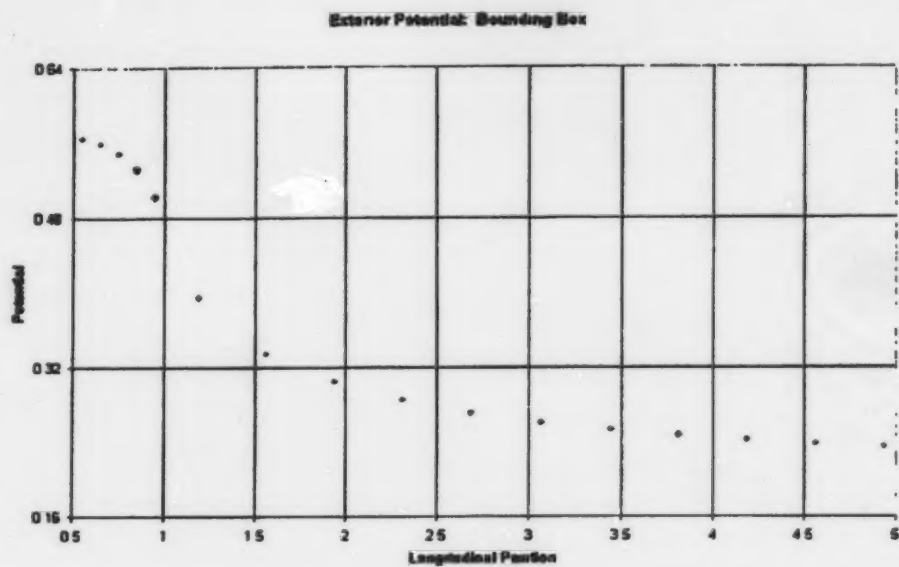


Figure 4.14a: CPBEM Interior Box Potential Results

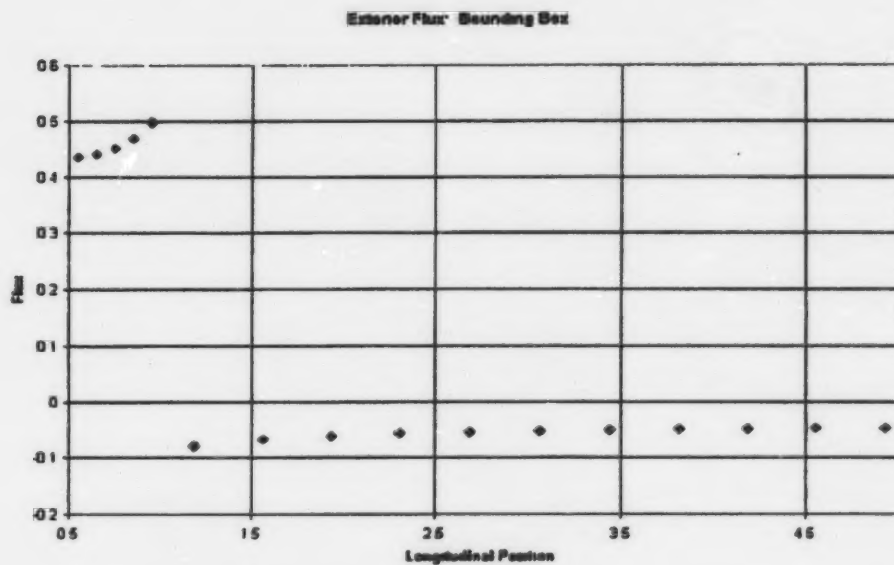


Figure 4.14b: CPBEM Interior Box Flux Results

5.0 RESULTS AND DISCUSSION

5.1 Polarization Resistance Results

The graphs in Figures 5.1- 5.5 show the combined (triplicate trial) potentiodynamic polarization resistance data collected for the nickel aluminum bronze specimen tests with naturally occurring seawater as the electrolytic medium. Anodic and cathodic polarization resistance data is represented as Figure (a) and Figure (b) for each test velocity, respectively. Figures 1 through 5 are ordered by increasing specimen test velocities (Figure 1- quiescent, Figure 2 - 0.33 m/s, Figure 3 - 0.62 m/s, Figure 4 - 1.19 m/s and Figure 5 - 2.33 m/s).

The relationship between applied potential and required current density for the initial portion of the curves for anodic tests conducted was approximated by a linear fit. For the quiescent tests conducted, this linear relationship was maintained to current densities of $10,000 \mu\text{A}/\text{cm}^2$ after which only minimal change in the current density was observed for increasing applied potentials. For the anodic polarization resistance tests conducted at increasing velocities, a reverse nose in the linear portion of the data was observed at approximately $100 \mu\text{A}/\text{cm}^2$. The positioning and morphology of this nose showed no significant variation as the velocity was increased from 0.33 m/s to 2.33 m/s. Similar to the quiescent tests conducted, at approximately $10,000 \mu\text{A}/\text{cm}^2$, little change was observed in the current density for increasing applied potential.

For the quiescent cathodic polarization resistance tests conducted, the current density increased from approximately $2 \mu\text{A}/\text{cm}^2$ to $100 \mu\text{A}/\text{cm}^2$ as the applied potential was increased from -300 mV to -600 mV versus a saturated calomel reference electrode (SCE). From -600 mV to 1100 mV only a minimal increase was observed in the current density. As the applied potential was increased above 100 mV the current density again resumed an increasing relationship. As the test velocity was increased from 0.33 m/s to 2.33 m/s the magnitude of the current density at the -600 mV knee showed an increasing trend from $300 \mu\text{A}/\text{cm}^2$ for 0.33 m/s to $1500 \mu\text{A}/\text{cm}^2$ at 2.33 m/s.

In general, from the tests conducted, the ASTM G-5 potentiodynamic test procedure produced excellent reproducibility. The triplicate tests conducted at each combination of test variables showed only minimal variation between tests. This observation is especially apparent from the cathodic test data presented.

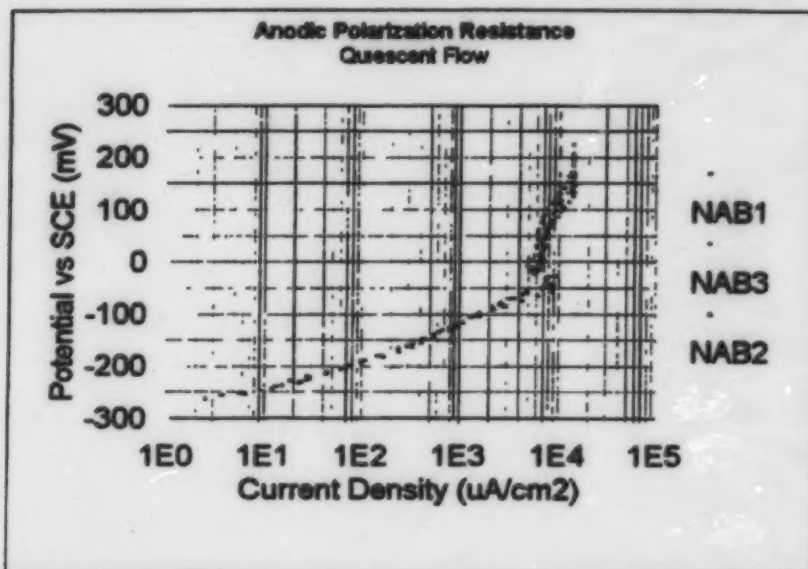


Figure 5.1 (a) - NAB anodic polarization resistance data generated for quiescent test conditions.

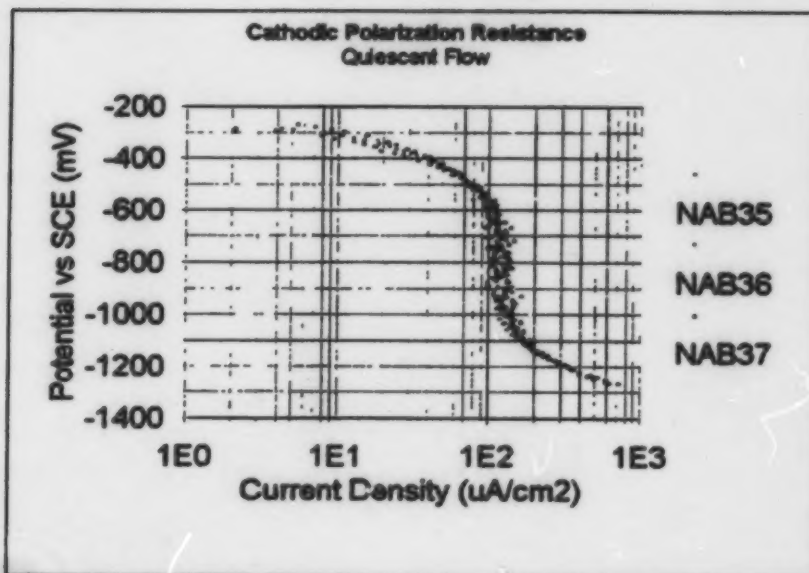


Figure 5.1 (b) - NAB cathodic polarization resistance data generated for quiescent test conditions.

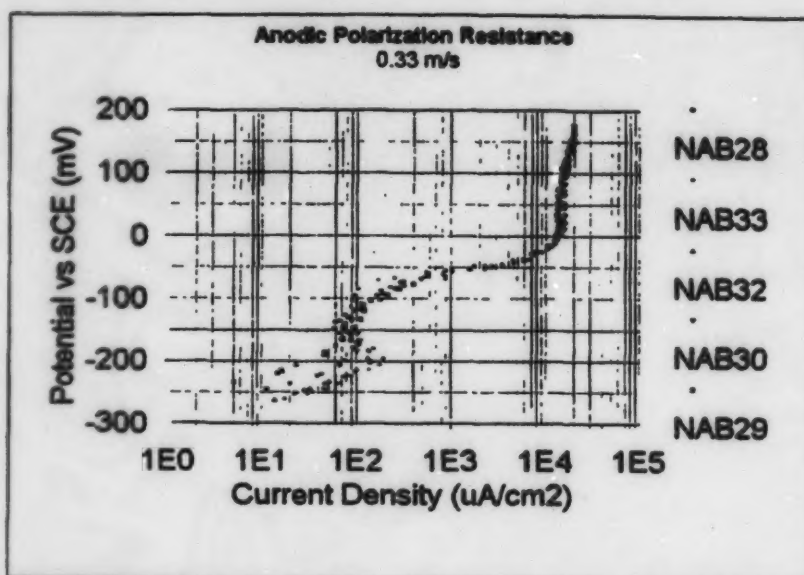


Figure 5.2 (a) - NAB anodic polarization resistance data generated for a specimen velocity of 0.33 m/s.

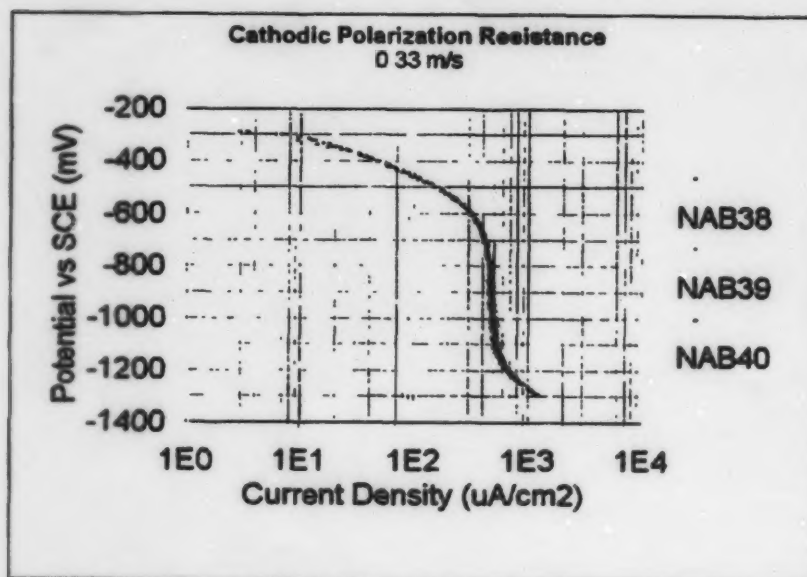


Figure 5.2 (b) - NAB cathodic polarization resistance data generated for a specimen velocity of 0.33 m/s.

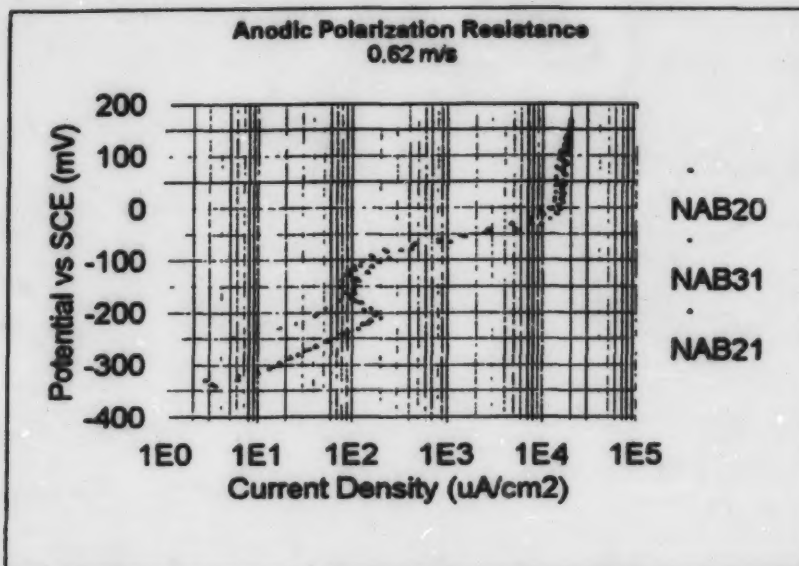


Figure 5.3 (a) - NAB anodic polarization resistance data generated for a specimen velocity of 0.62 m/s

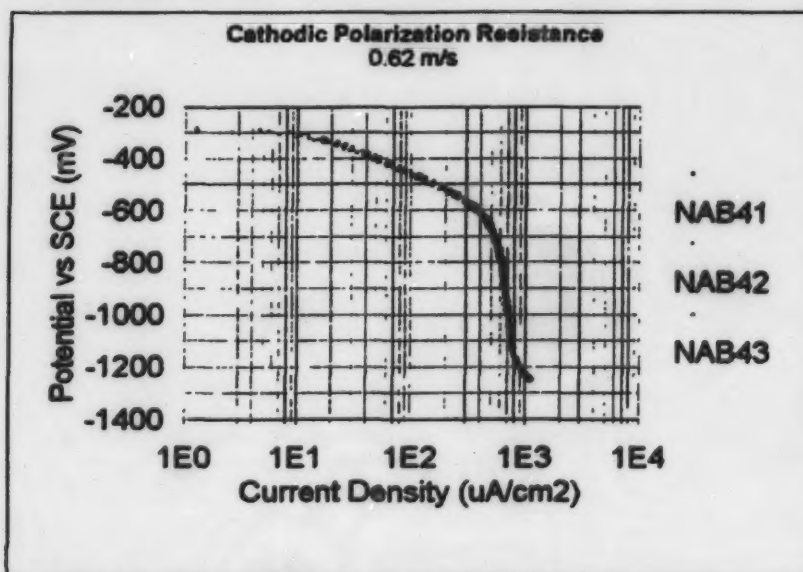


Figure 5.3 (b) - NAB cathodic polarization resistance data generated for a specimen velocity of 0.62 m/s

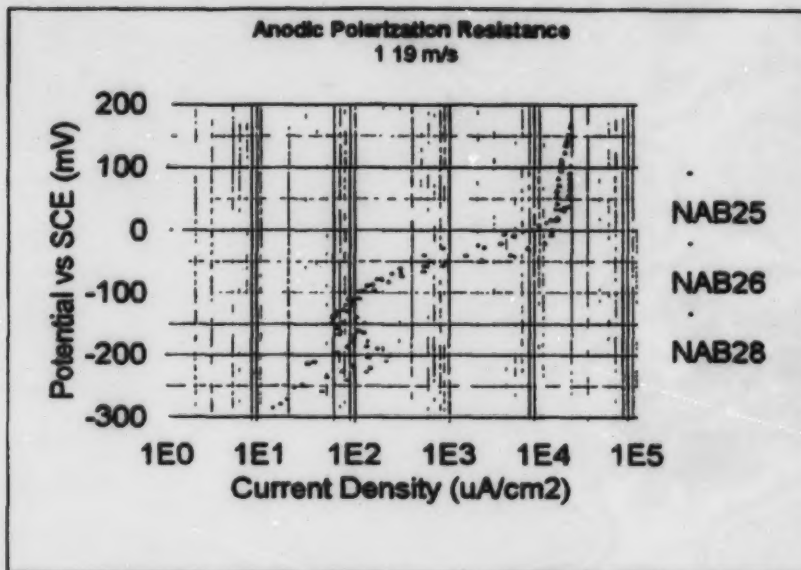


Figure 5.4 (a) - NAB anodic polarization resistance data generated for a specimen velocity of 1.19 m/s

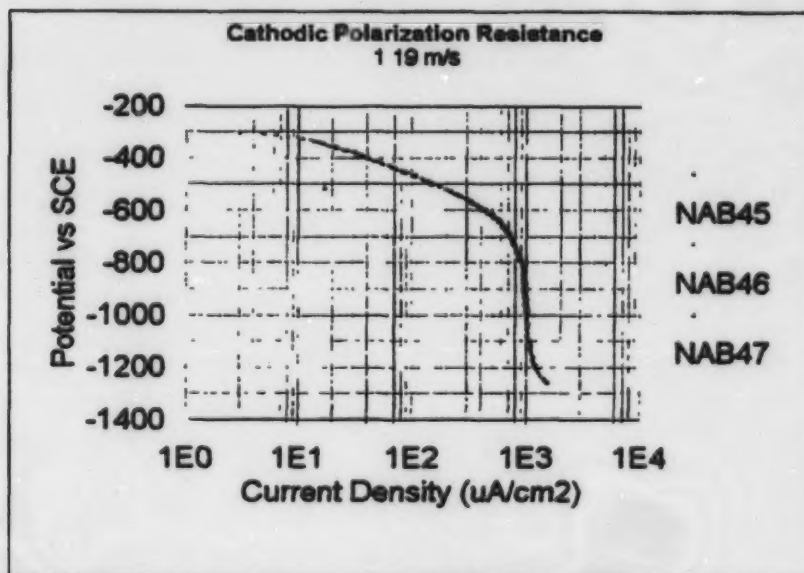


Figure 5.4 (b) - NAB cathodic polarization resistance data generated for a specimen velocity of 1.19 m/s

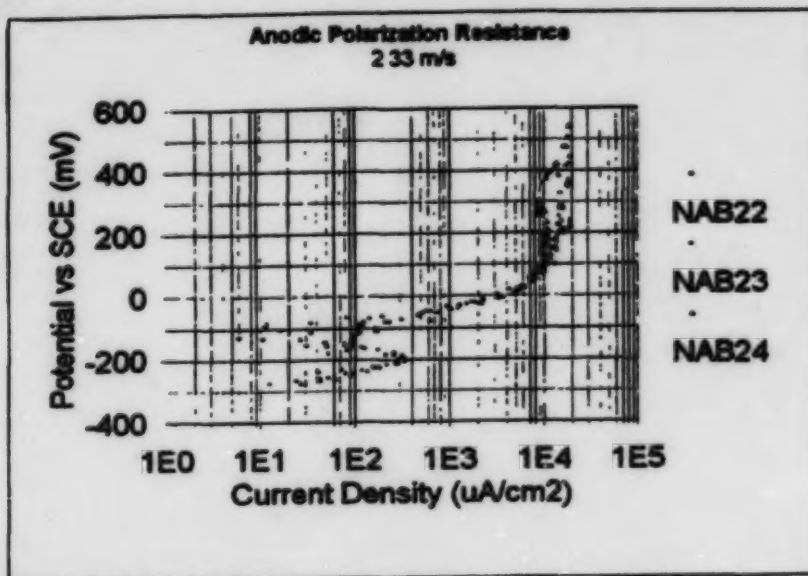


Figure 5.5 (a) - NAB anodic polarization resistance data generated for a specimen velocity of 2.33 m/s

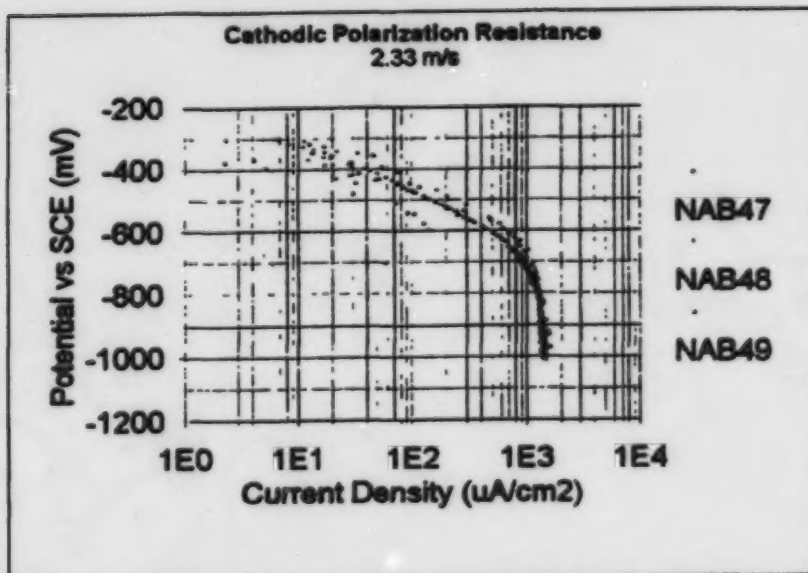


Figure 5.5 (b) - NAB cathodic polarization resistance data generated for a specimen velocity of 2.33 m/s

5.2 Physical Scale Modelling Results

Tables 5.1 through 5.4 contain the longitudinal reference electrode potentials and aft anode current demand for the two differing ICCP model anode/references electrode configurations under static and dynamic conditions. Tables 5.1 and 5.2 contain the results for trials where reference electrode 10 was used as the feedback signal (aft-aft configuration for CPF) for 0 and 3450 RPM propeller velocities, respectively. Tables 5.3 and 5.4 contain the results for the configurations where reference electrode 8 was used as the feedback signal (mid-aft configuration for CPF) for 0 and 3450 RPM propeller velocities, respectively. For each configuration and velocity combination, the results for three differing tests at potentials bracketing the operational range of acceptable protection were recorded. For all configurations and velocities tested, the data indicates that as the applied potential increases, the current demand increases. Since the NAB propellers are the only exposed metallic structure during these trials, this observation is consistent with the cathodic NAB polarization resistance generated and presented in the previous section.

For the two static trials (0 RPM propeller velocities), the developed feedback control circuitry provided stable control of the model currents. However, for the dynamic test conducted at 3450 RPM a minor oscillation was observed in the command/feedback relationship. The likely source of this oscillation is inadequate shaft grounding at higher rotational velocities.

Table 5.1 - 0 RPM Velocity, Reference Ag/AgCl, Conductivity 415-420 $\mu\text{mho/cm}$, Feedback Ref 10

Cmd (V)	Cur (A)	Ref 1 (mV)	Ref 2 (mV)	Ref 3 (mV)	Ref 4 (mV)	Ref 5 (mV)	Ref 6 (mV)	Ref 7 (mV)	Ref 8 (mV)	Ref 9 (mV)	Ref 10 (mV)
-0.60	1.185	638	646	638	648	639	646	641	657	664	606
-0.80	2.29	845	848	845	850	845	848	849	858	896	792
-1.00	3.15	1061	1065	1060	1067	1061	1067	1067	1078	1111	980

Table 5.2 - 3450 RPM Velocity, Reference Ag/AgCl, Conductivity 415-420 $\mu\text{mho/cm}$, Feedback Ref 10

Cmd (V)	Cur (A)	Ref 1 (mV)	Ref 2 (mV)	Ref 3 (mV)	Ref 4 (mV)	Ref 5 (mV)	Ref 6 (mV)	Ref 7 (mV)	Ref 8 (mV)	Ref 9 (mV)	Ref 10 (mV)
-0.60	1.91	666	667	667	667	667	664	668	680	683	605
-0.80	2.80	854	856	854	856	853	855	853	887	921	787
-1.00	3.70	*1228	1240	1237	1238	1213	1235	1236	1271	1299	1114

* Input data showed significant variation (observation of command/feedback relationship experienced oscillation).

Table 5.3 - 0 RPM Velocity, Reference Ag/AgCl, Conductivity 415-420 $\mu\text{mho/cm}$, Feedback Ref 8

Cmd (V)	Cur (A)	Ref 1 (mV)	Ref 2 (mV)	Ref 3 (mV)	Ref 4 (mV)	Ref 5 (mV)	Ref 6 (mV)	Ref 7 (mV)	Ref 8 (mV)	Ref 9 (mV)	Ref 10 (mV)
-0.60	0.93	601	603	603	603	601	603	605	606	614	582
-0.80	1.95	778	783	783	783	782	783	782	791	813	728
-1.00	2.58	946	944	944	943	948	943	941	990	1000	869

Table 5.4 - 3450 RPM Velocity, Reference Ag/AgCl, Conductivity 415-420 $\mu\text{mho/cm}$, Feedback Ref 8

Cmd (V)	Cur (A)	Ref 1 (mV)	Ref 2 (mV)	Ref 3 (mV)	Ref 4 (mV)	Ref 5 (mV)	Ref 6 (mV)	Ref 7 (mV)	Ref 8 (mV)	Ref 9 (mV)	Ref 10 (mV)
-0.60	1.28	597	600	600	600	598	600	601	605	615	571
-0.80	1.86	875	887	853	843	876	841	867	*818	890	787
-1.00	2.76	972	949	981	959	948	946	966	*1000	1020	902

* Input data showed significant variation (observation of command/feedback relationship experienced oscillation).

In general, it is observed that potentials remain relatively constant to the fore of reference electrode 7 which is located in front of the aft anodes. This observation is consistent with the position of the propellers which is aft of the aft anodes combined with the high dielectric capacity of the hull form. It is also observed that the current demand required by the propellers produces an area of decreased potential aft of the propellers. For the configurations which used the mid-aft reference electrode as the feedback signal, the level of protection behind the propellers (for a -0.8V command signal) is reduced to marginal levels for the static test conducted. The data indicates that positioning the feedback reference electrode aft of the propellers resolves under protection issues behind the propellers but has the effect of increasing the level of potential fore of the rear anodes. For the -0.8 V static test conducted, these levels did not, however, increase to the level where paint degradation is significant.

Increasing the velocity for a given configuration has the effect of increasing the current demand required to protect the propellers which again is consistent with the trends observed in the polarization resistance tests conducted on the NAB propeller material. This increased current demand for the dynamic tests results in an longitudinal potential profile with marginally higher levels of applied potentials to the fore of the aft anodes.

5.3 Computer Modelling Results

The geometric model of the CPF was generated using the CPBGEN pre-processor. In order to take advantage of symmetry, only one-half of the ship was panelized, requiring a total of 611 quadrilateral boundary element panels (see Figures 5.6 and 5.7). Although not required for this particular series of numerical trials, the model included local mesh refinements for two anodes (see Figure 5.6), the first located approximately 47 meters aft of the forward perpendicular, and the second located a few meters forward of the propeller (cathode). For the purposes of this study, only the aft anode was activated.

Figure 5.5 represents a typical comparison between the potentials predicted by the computer model and recorded PSM potentials using the ASTM G5 potentiodynamic polarization resistance data as input to the computer model. Using the ASTM G5 data generally did not result in a good correlation between the computer and PSM results. This observation was attributed to the inability of a "short term test" to predict current densities which accurately reflect field observations. It is recommended for future studies, that laboratory polarization resistance data be generated using a "long term potentiostatic test procedure.

For this study, the NAB propellers were the only galvanically active metal attached to the model, thus polarization resistance data used as input to the computer model was generated directly from the propellers attached to the PSM model. This was achieved by using the computer model to accurately assess the potential difference between the propeller material and an adjacent reference electrode.

The polarization curve data used in the analysis is provided below in Table 5.5. This data was obtained directly from the experimental analysis (see chapter 4), and represents the static, or quiescent, case (i.e.: zero propeller velocity).

Table 5.5: Polarization Curve Data

Potential (mV)	Current Density (micro A / cm ²)
547.9	14.79
562.6	18.85
656.9	31.02
708.5	36.43
775	41.04
864.7	50.11

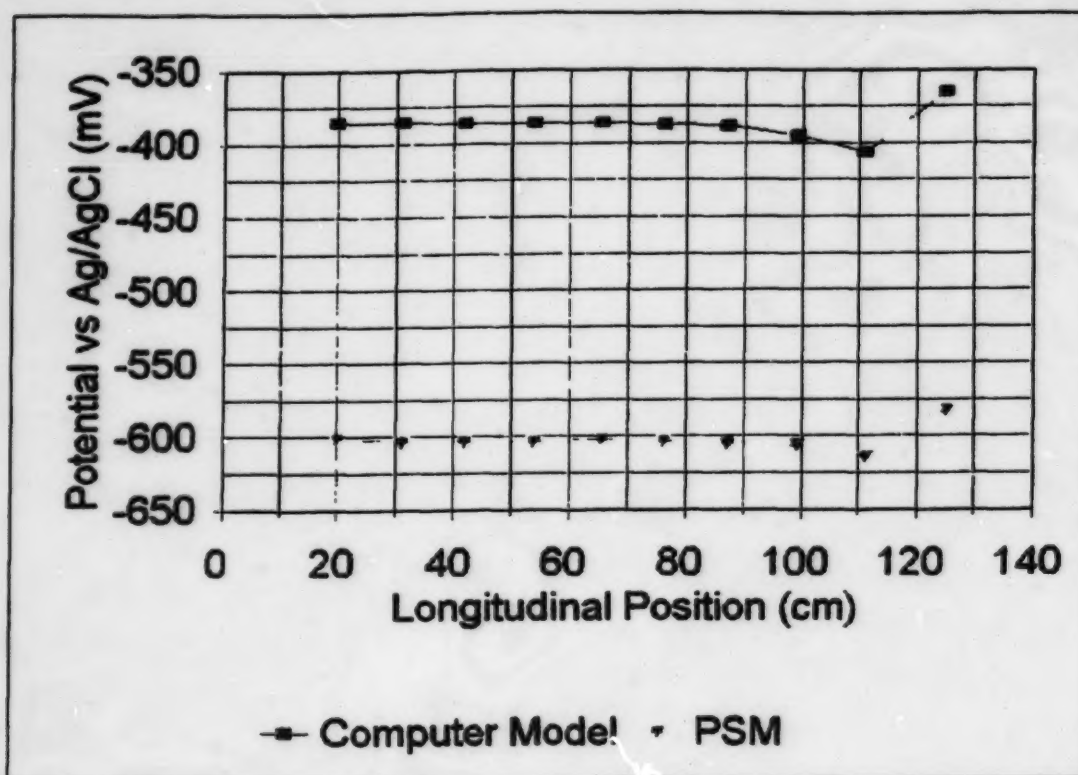


Figure 5.5 - Hull potentials along the longitudinal axis of the PSM model compared to the computer simulation using potentiodynamic polarization data generated using ASTM G5 (Quiescent flow with reference electrode 8 feedback potential of -0.6V).

For the purposes of this study, numerical simulations were performed in order to predict the effect of varying the anode current. The anode current levels considered are provided below in Table 5.6. Contour plots of the surface potentials for each of the six quiescent and dynamic cases are also provided below in Figures 5.8 – 5.13 and 5.14 – 5.19 respectively.

Table 5.2: Aft Anode Current Levels

Numerical Trial Number	Anode Current
1	0.93 mA
2	1.95 mA
3	2.58 mA
4	1.185 mA
5	2.29 mA
6	3.15 mA



Figure 5.6: Boundary Element Mesh of CPF Model



Figure 5.7: Close up of Aft Node / Propeller (Cathode) Regions



Figure 5.8: Surface Potentials Computed for Anode Current of 0.93 mA (quiescent polarization data).

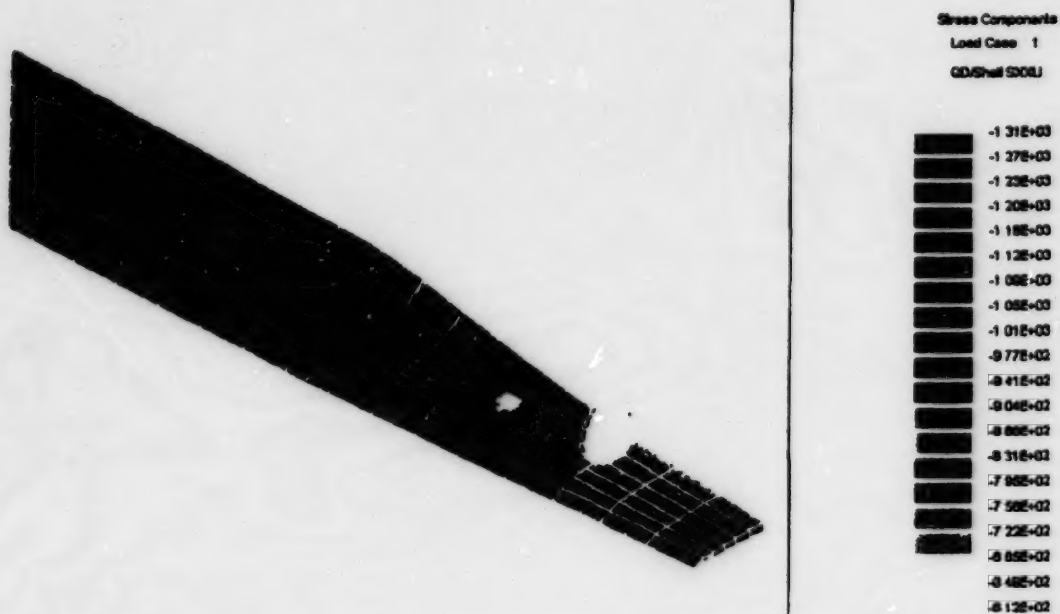


Figure 5.9: Surface Potentials Computed for Anode Current of 1.95 mA (quiescent polarization data).

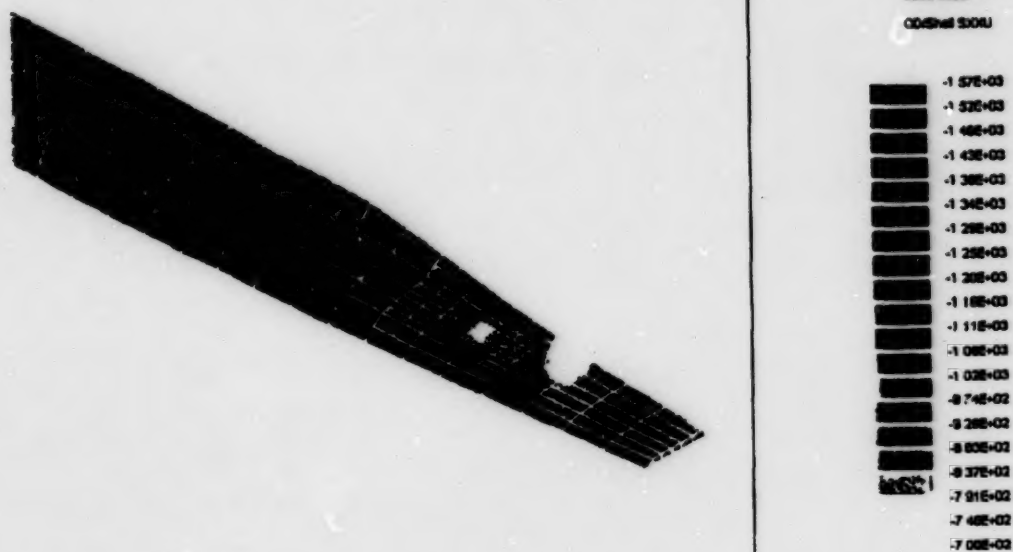
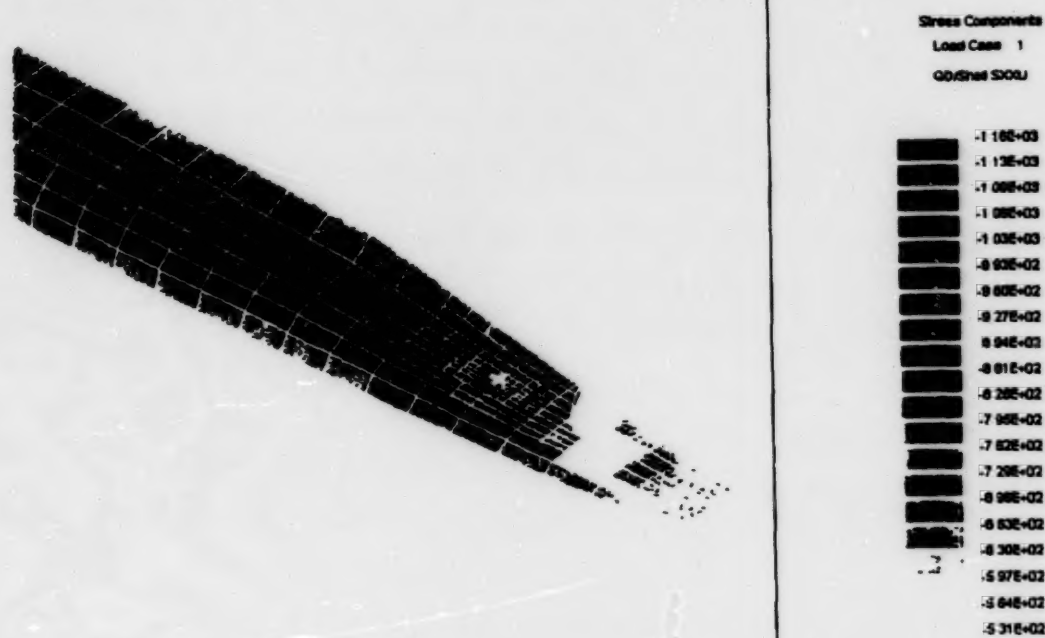


Figure 5.10: Surface Potentials Computed for Anode Current of 2.58 mA (quiescent polarization data).



Figure

Figure 5.11: Surface Potentials Computed for Anode Current of 1.185 mA (quiescent polarization data).

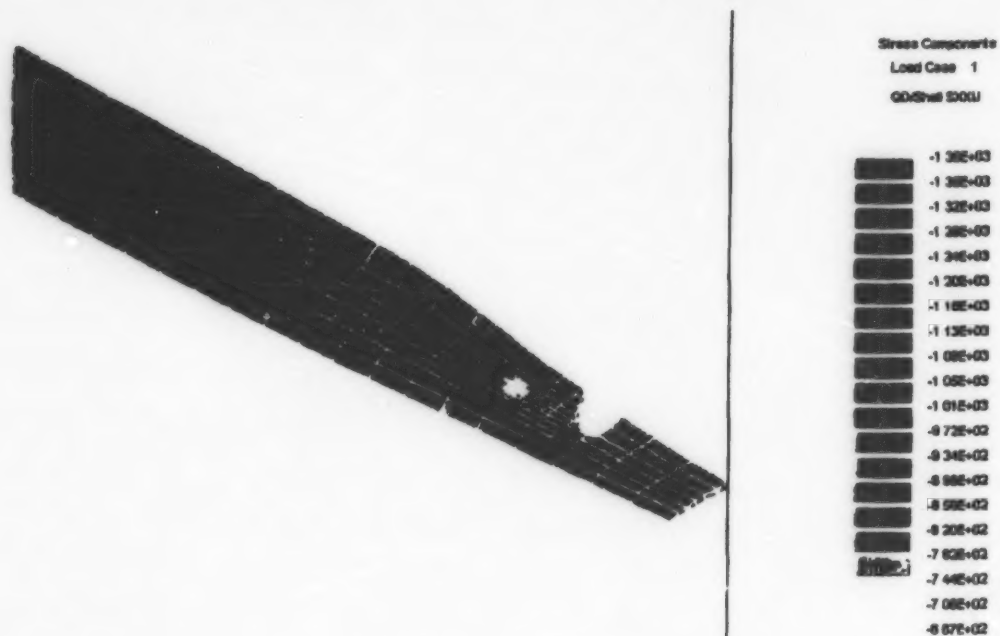


Figure 5.12: Surface Potentials Computed for Anode Current of 2.29 mA(quietest polarization data).

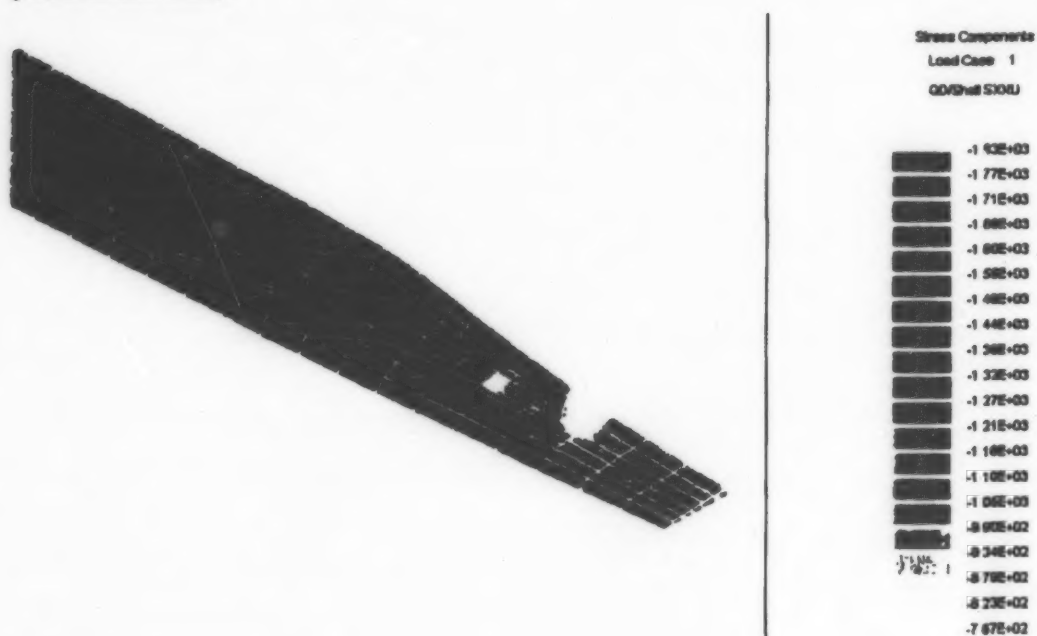


Figure 5.13: Surface Potentials Computed for Anode Current of 3.15 mA(quietest polarization data).

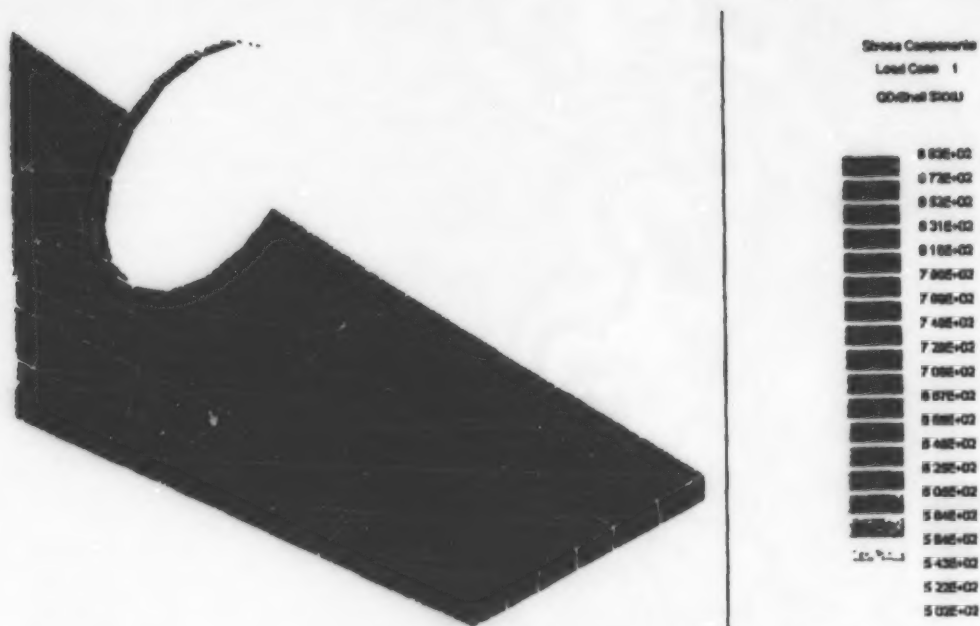


Figure 5.14: Surface Potentials Computed for Anode Current of 1.91 mA(dynamic polarization data).

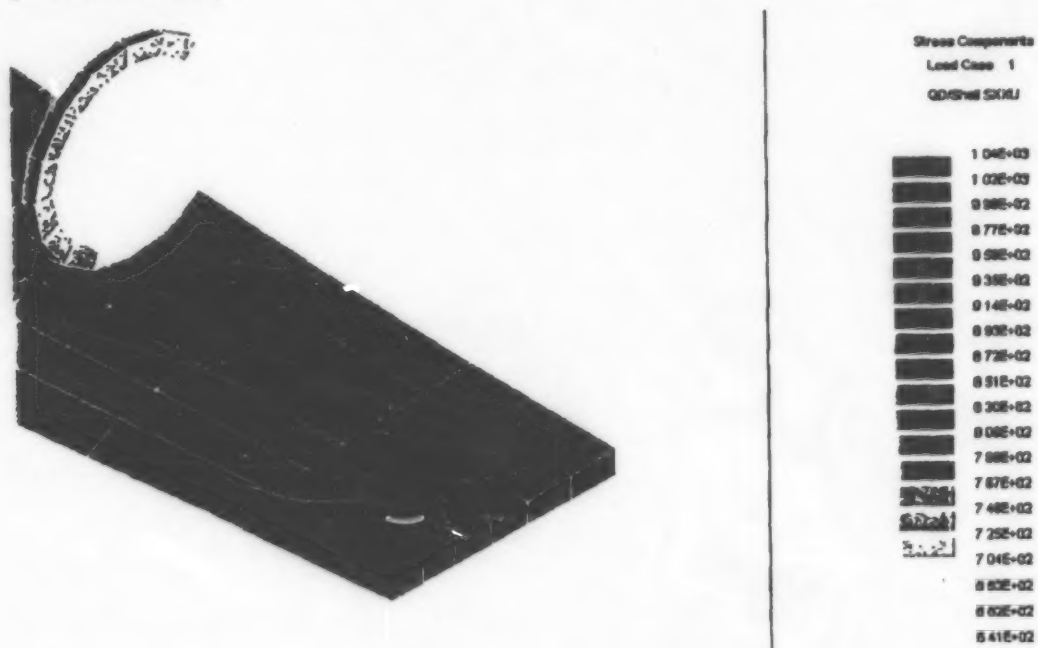


Figure 5.15: Surface Potentials Computed for Anode Current of 2.80 mA(dynamic polarization data).



Stress Components
Load Case: 1
QD/Shell (SOL)

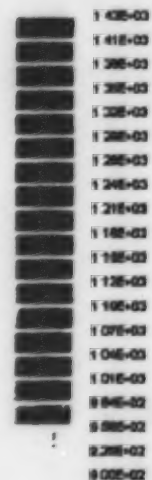
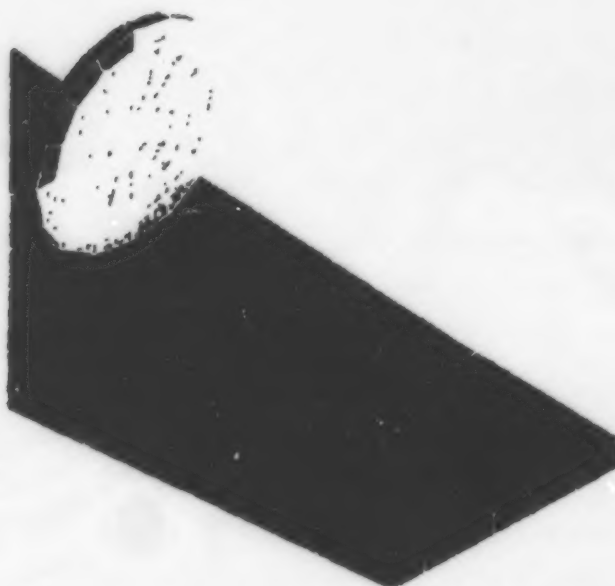


Figure 5.16: Surface Potentials Computed for Anode Current of 1.28 mA(dynamic polarization data).



Stress Components
Load Case: 1
QD/Shell (SOL)

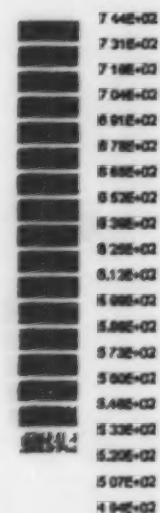


Figure 5.17: Surface Potentials Computed for Anode Current of 1.86 mA(dynamic polarization data).



Stress Component
Load Case 1
QD/Shell SOLU

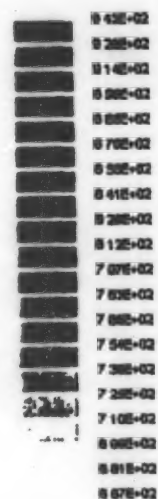
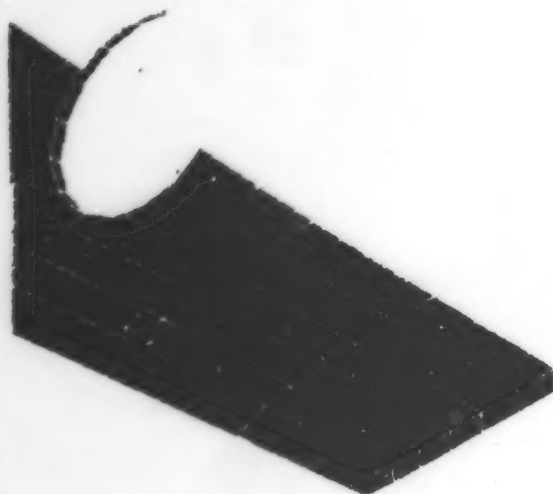


Figure 5.18: Surface Potentials Computed for Anode Current of 2.76 mA(dynamic polarization data).



Stress Component
Load Case 1
QD/Shell SOLU

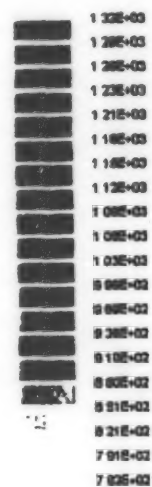


Figure 5.19: Surface Potentials Computed for Anode Current of 1.91 mA(dynamic polarization data).

5.4 Comparison of PSM, CPBEM and BEASY Hull Potential Profiles

The primary objective of this study was to develop two independent methodologies for generating hull potential profiles for impressed current cathodic systems (ICCP). In the execution of experimental program, results were generated by both physical scale modelling (PSM) and computer simulations. Codes utilized to generate the computer simulations included both CPBEM (a code developed by DREA/DL) and BEASY (a software code which has been used as a benchmark code by several NATO countries). This section compares PSM and the analytical results generated for the PSM configurations evaluated.

Figures 5.20 - 5.25 and 5.26 - 5.31 are graphical comparisons of the PSM, CPBEM and BEASY results for the quiescent and dynamic PSM model configurations tested respectively. Graph (a) in each configuration shows the potentials generated for various positions along the longitudinal axis of the CPF hull form. Graph (b) for each configuration represents the differences obtained between the hull potentials generated by the two computer codes employed (CPBEM and BEASY) and the PSM reference electrode potentials.

For the quiescent tests, both the CPBEM and BEASY results show excellent agreement with the PSM potentials. In general, potentials generated by CPBEM were within 5 percent of the potentials recorded using the PSM modelling methodology. BEASY generally produced a closer agreement with the PSM results than CPBEM. Potentials generated by BEASY were normally within 2 percent of the respective PSM potential. It has been postulated that the non-linearity of the polarization resistance data used as input may account for a portion of the differences observed between the two codes. Incorporating a more sophisticated solver algorithm into the CPBEM code would bring the agreement within the accuracy exhibited by BEASY for these trials.

For both relationships, the PSM data indicates that a portion of the difference observed between the PSM and computer simulated results can be attributed to the approximately 5 mV scatter observed in the PSM feedback signals. Scatter could be reduced by modifying the ICCP hardware to include a programmable gain amplifier in the feedback circuits and a sample and hold latching circuit prior to the A/D circuitry. A programmable gain amplifier would allow for software auto-ranging which can be software configured to maintain maximum possible signal levels being input to the A/D. A sample and hold circuit prior to the A/D stabilizes the input signal to the A/D. A/D's do not perform well under circumstances where the A/D input buffer experiences significant dV/dt fluctuations during the conversion process.

Similar to the quiescent tests, both CPBEM and BEASY predictions produced excellent agreement with the PSM potentials recorded for the dynamic configurations evaluated. In general, both CPBEM and BEASY were within 5 percent of the potentials recorded using the PSM facility. In the dynamic case, the absence of a difference between the performance of CPBEM and BEASY is attributed to the electrical noise generated by the contact used to ground the propeller shafts to the ICCP hardware.

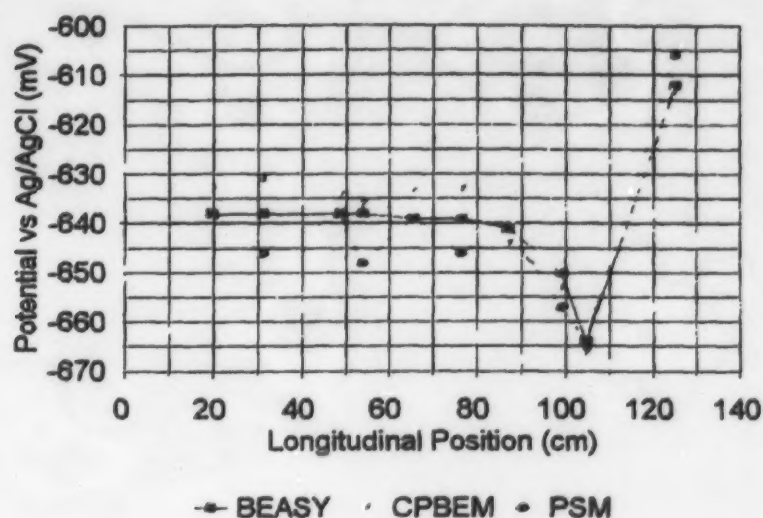


Figure 5.20a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Quiescent flow with reference electrode 10 feedback potential of 0.6V).

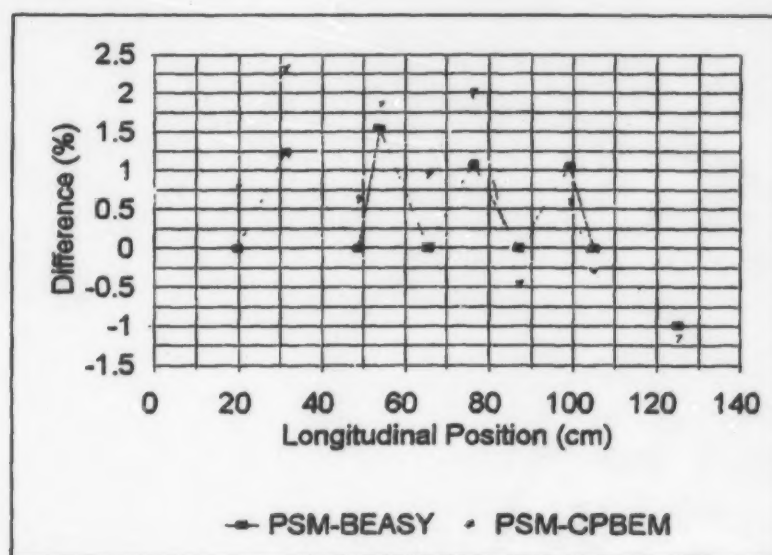


Figure 5.20b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Quiescent flow with reference electrode 10 feedback potential of 0.6V).

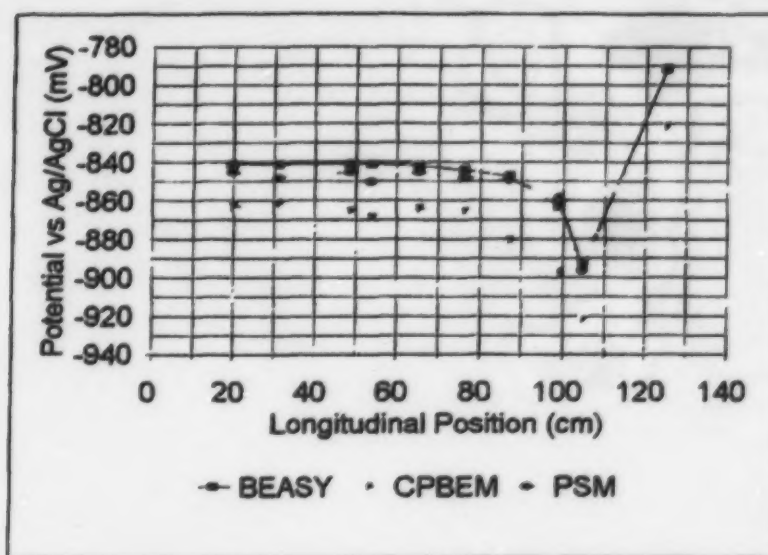


Figure 5.21a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Quiescent flow with reference electrode 10 feedback potential of 0.8V).

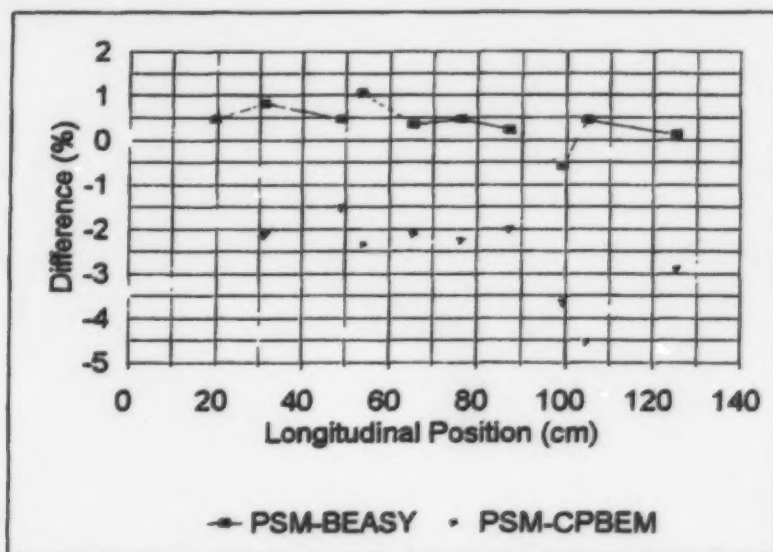


Figure 5.21b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Quiescent flow with reference electrode 10 feedback potential of 0.8V).

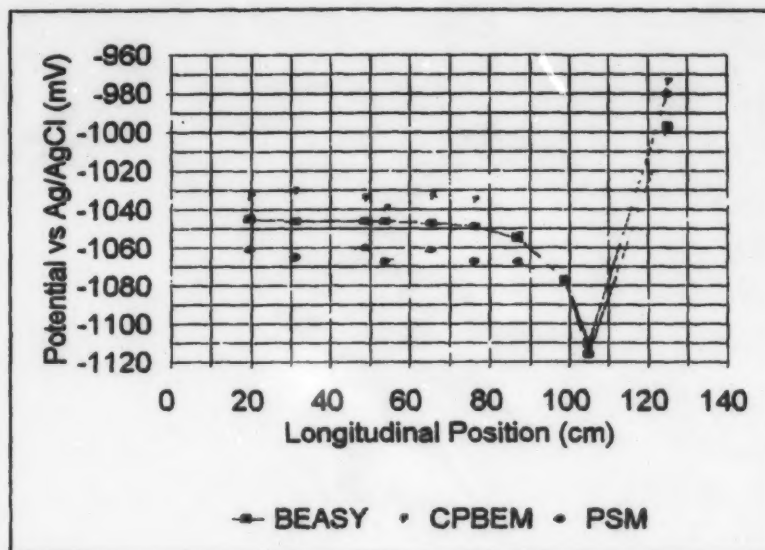


Figure 5.22a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Quiescent flow with reference electrode 10 feedback potential of 1.0V).

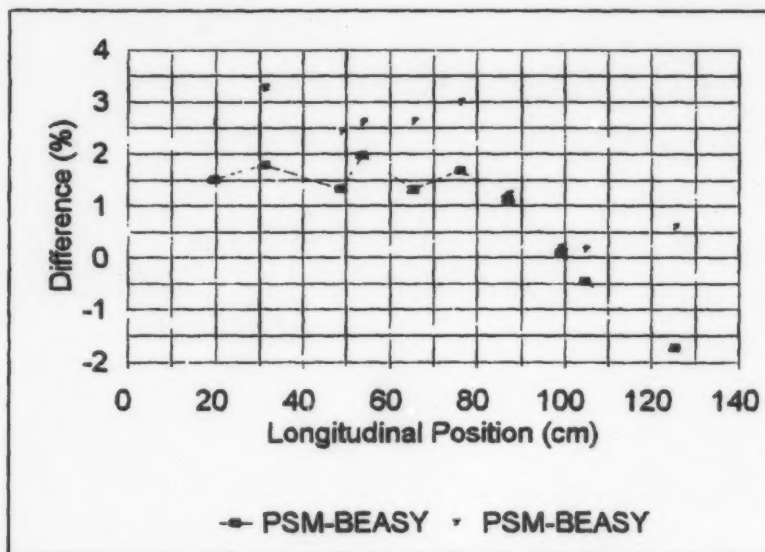


Figure 5.22b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Quiescent flow with reference electrode 10 feedback potential of 1.0V).

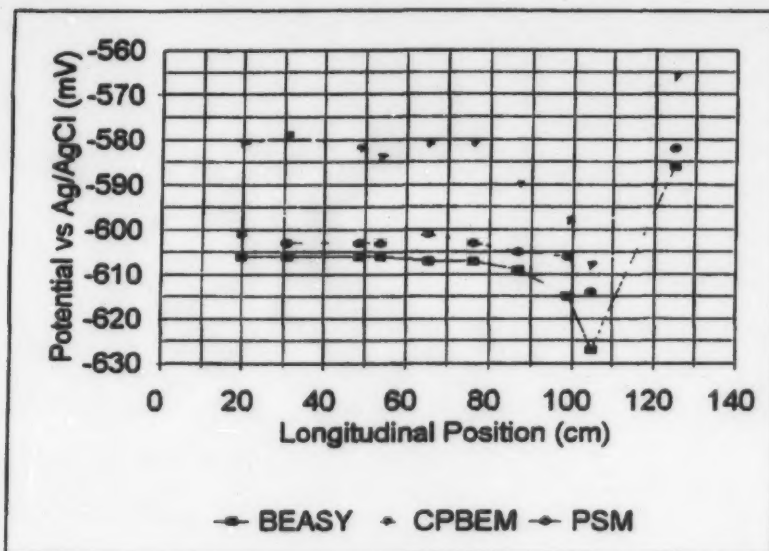


Figure 5.23a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Quiescent flow with reference electrode 8 feedback potential of 0.6V).

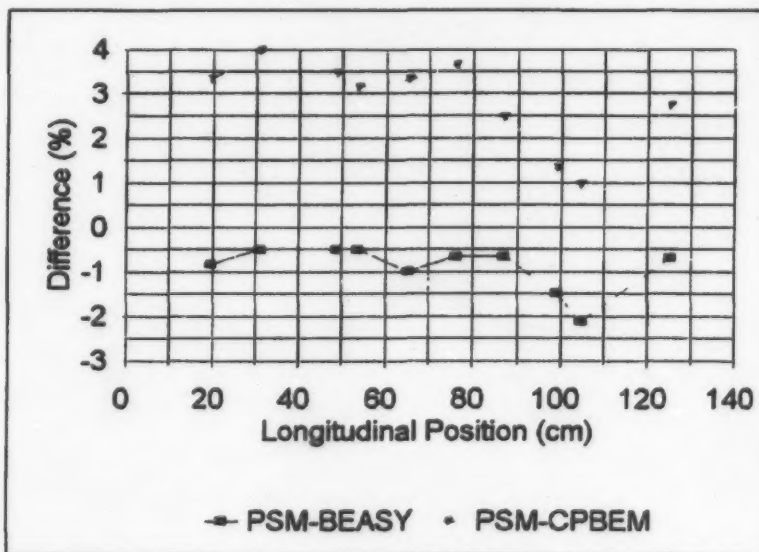


Figure 5.23b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Quiescent flow with reference electrode 8 feedback potential of 0.6V).

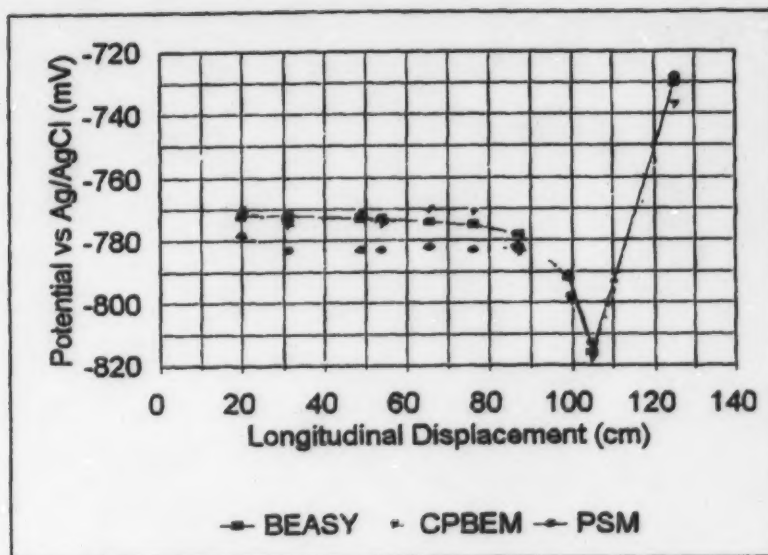


Figure 5.24a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Quiescent flow with reference electrode 8 feedback potential of 0.8V).

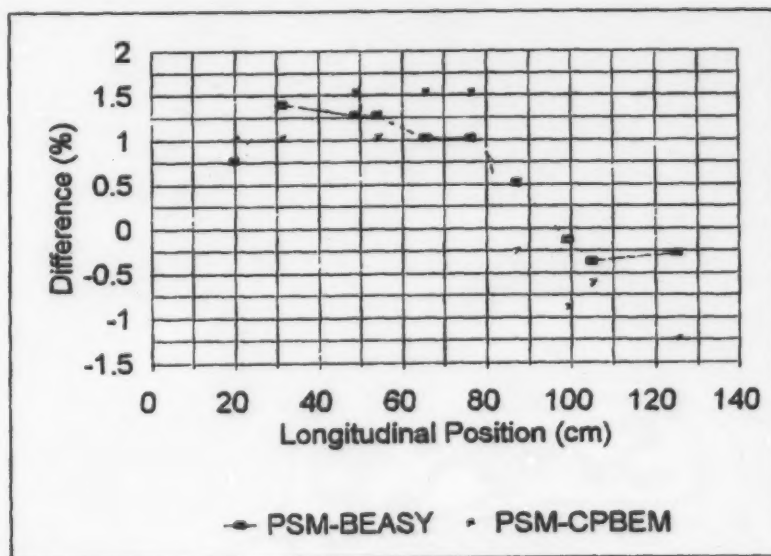


Figure 5.24b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Quiescent flow with reference electrode 8 feedback potential of 0.8V).

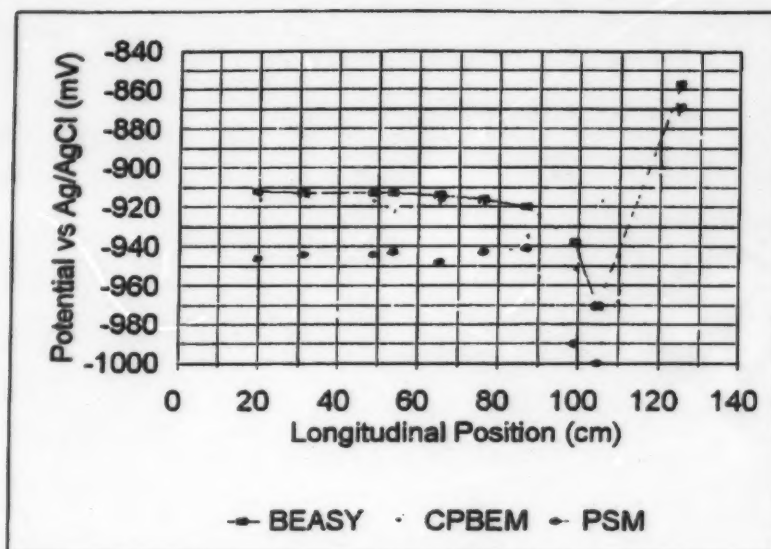


Figure 5.25a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Quiescent flow with reference electrode 8 feedback potential of 1.0V).

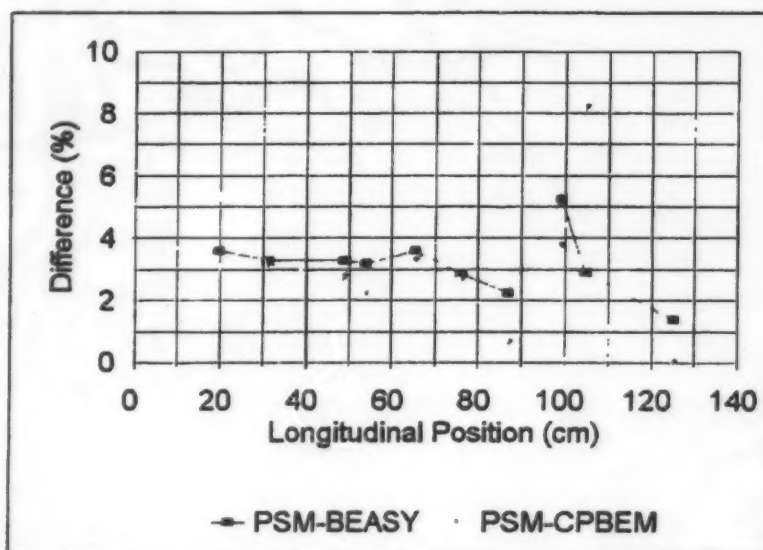


Figure 5.25b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Quiescent flow with reference electrode 8 feedback potential of 1.0V).

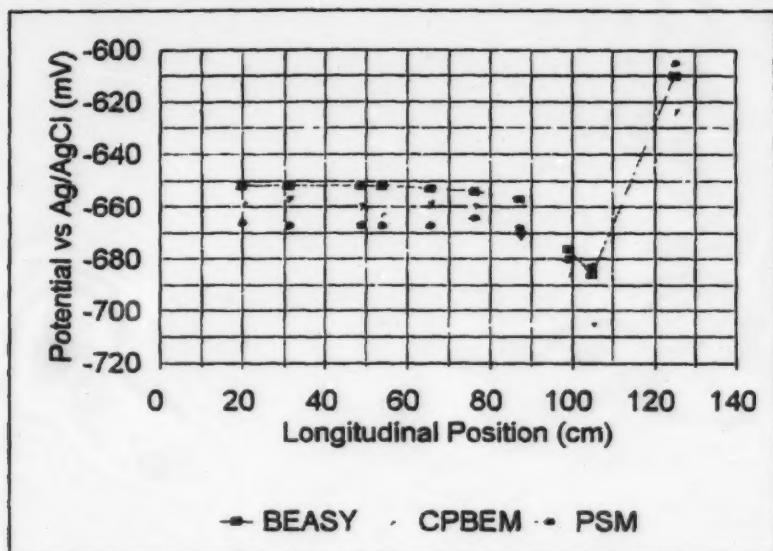


Figure 5.26a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Dynamic flow with reference electrode 10 feedback potential of 0.6V).

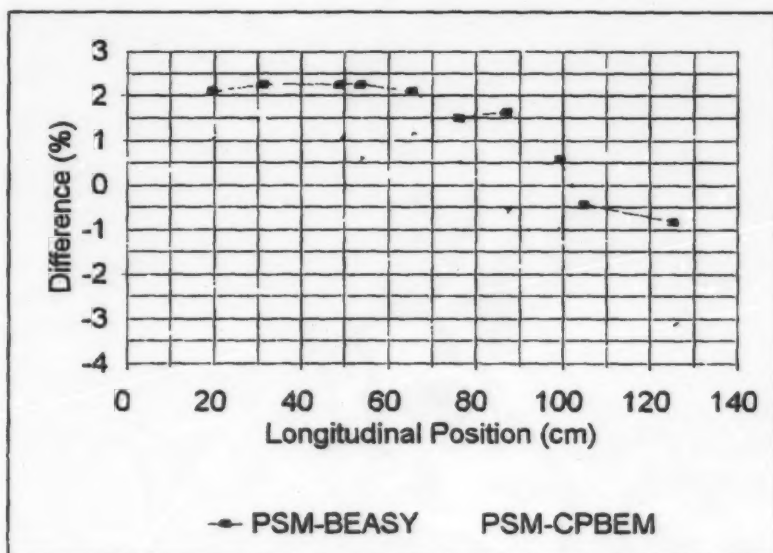


Figure 5.26b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Dynamic flow with reference electrode 10 feedback potential of 0.6V).

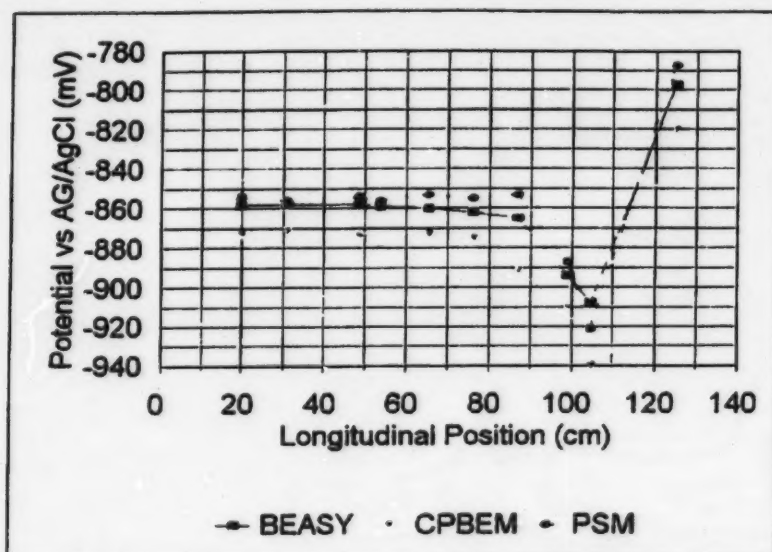


Figure 5.27a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Dynamic flow with reference electrode 10 feedback potential of 0.8V).

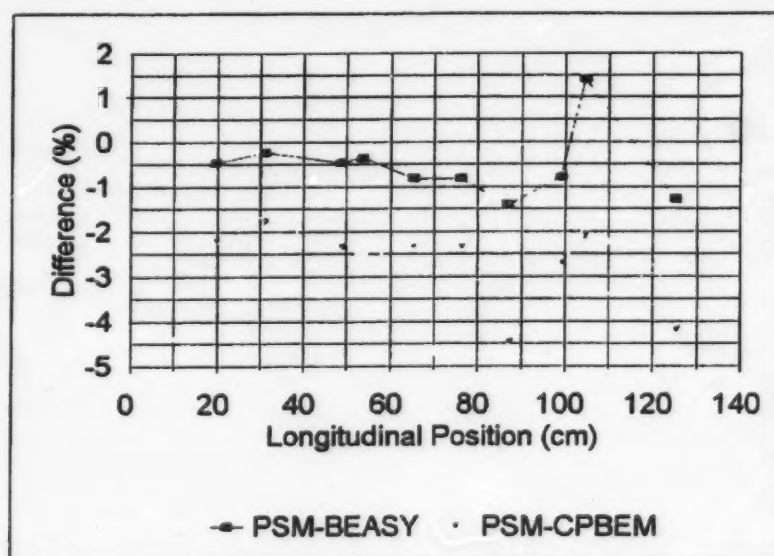


Figure 5.27b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Dynamic flow with reference electrode 10 feedback potential of 0.8V).

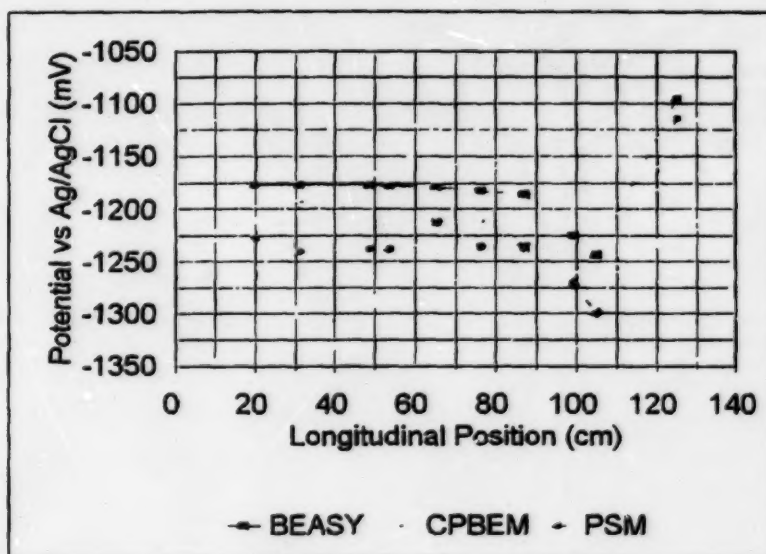


Figure 5.28a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Dynamic flow with reference electrode 10 feedback potential of 1.0V).

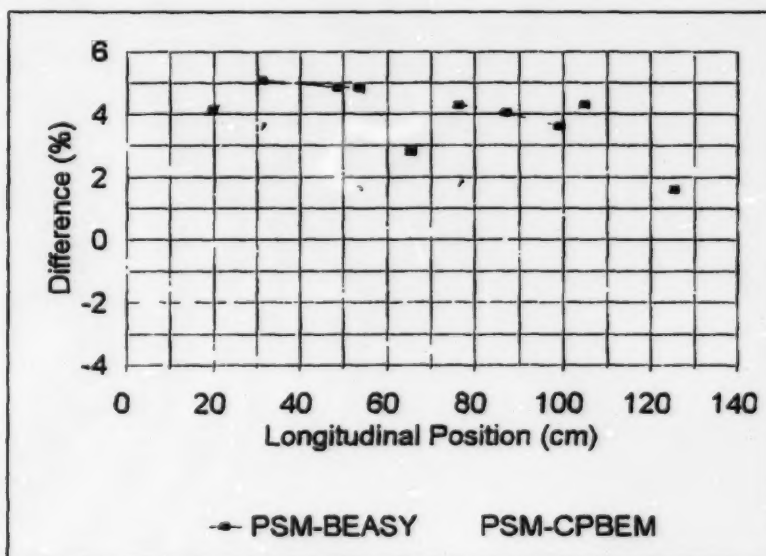


Figure 5.28b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Dynamic flow with reference electrode 10 feedback potential of 1.0V).

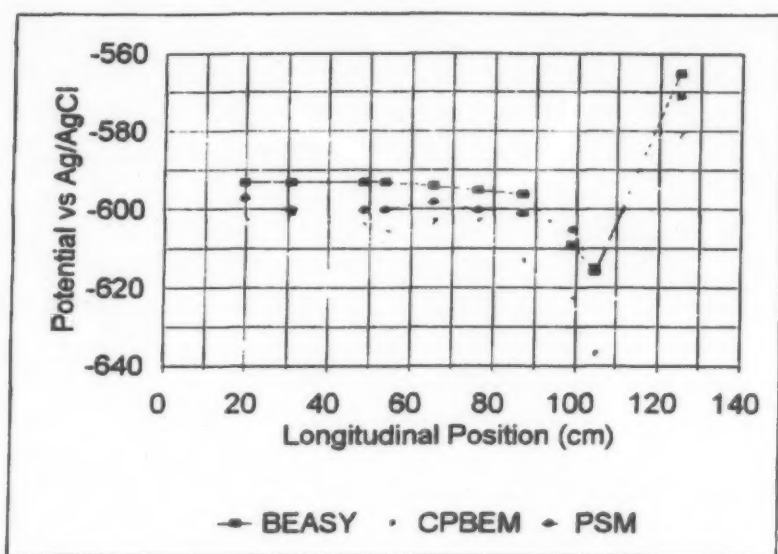


Figure 5.29a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Dynamic flow with reference electrode 8 feedback potential of 0.6V).

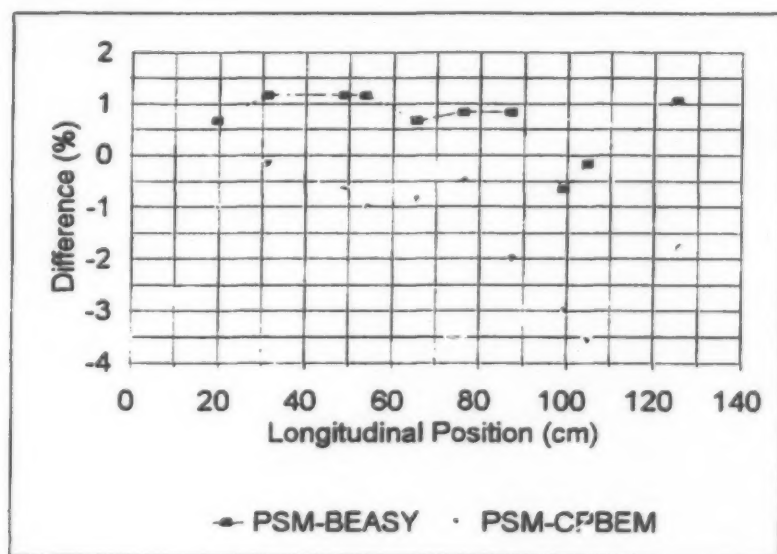


Figure 5.29b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Dynamic flow with reference electrode 8 feedback potential of 0.6V).

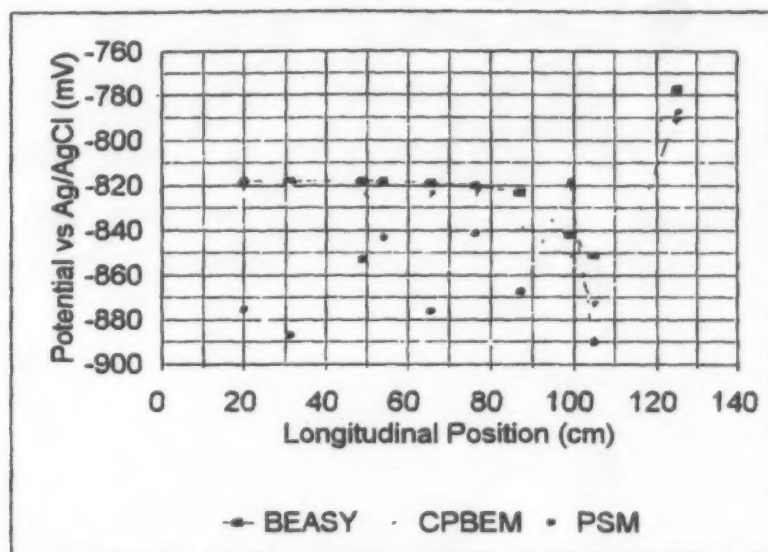


Figure 5.30a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Dynamic flow with reference electrode 8 feedback potential of 0.8V).

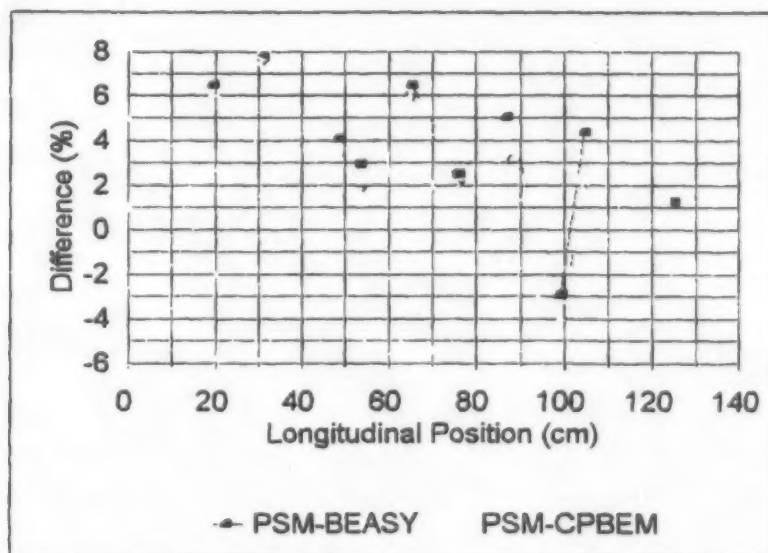


Figure 5.30b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Dynamic flow with reference electrode 8 feedback potential of 0.8V).

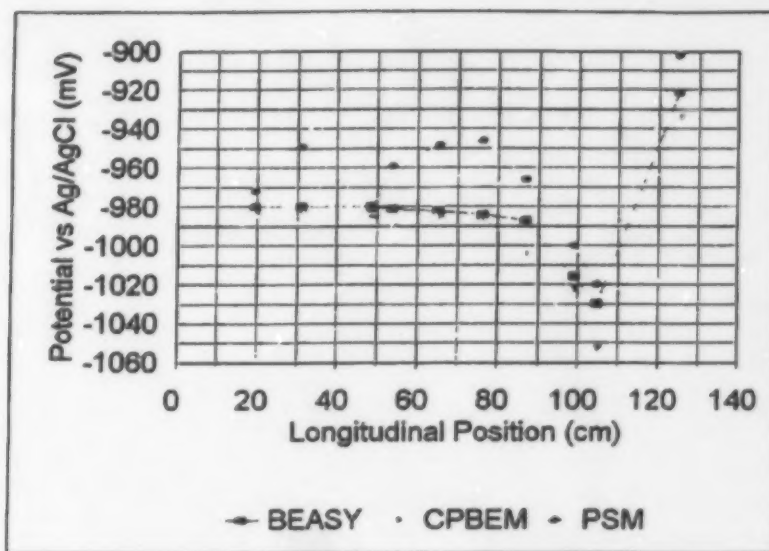


Figure 5.31a - Hull potentials along the longitudinal axis of the PSM model compared to the CPBEM and BEASY predictions. Model configuration (Dynamic flow with reference electrode 8 feedback potential of 1.0V).

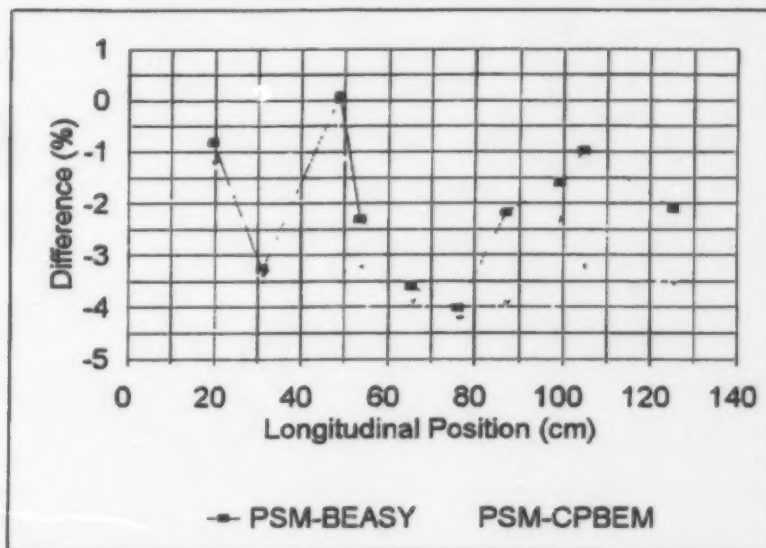


Figure 5.31b - Percent difference between PSM, CPBEM and BEASY predictions along the longitudinal axis of the model. Model configuration (Dynamic flow with reference electrode 8 feedback potential of 1.0V).

6.0 CONCLUSIONS

A comprehensive program was conducted to develop two independent methodologies for generating hull potential profiles for impressed current cathodic protection systems. The two methodologies developed were physical scale modelling and computer simulations using CPBEM and BEASY software suites. Conducting the physical scale modelling trials required upgrading the previously inactive PSM facility. The upgrades included designing and developing a digital communication protocol for the system, controllers for the PSM analog devices and controllers for the ICCP model. A 1/100 scale model of CPF was fabricated and instrumented for comparison with the computer simulations. Several inferences can be drawn from the results generated from this study. These inferences include:

The digital communications protocol designed and fabricated to control the ICCP/PSM facility significantly reduces the level of RF noise experienced by the previous analog sensor bus configuration.

Several improvements are, however, recommended to the hardware software suite to improve the signal quality. These include adding sample and hold circuitry to the front end of the A/D convertor and adding a programmable gain amplifier circuit to the front end of the A/D convertor to allow for software auto ranging (this will improve the accuracy at very low signal levels).

The polarization resistance testing indicated that for the NAB material tested, current density demand increases in a non linear relationship with potential. Current density requirements also increases as test specimen velocity increases from 0 m/s to 2.33 m/s. Future work should focus on producing long term potenti-static polarization results for NAB and steel (both coated and uncoated).

Both CPBEM and BEASY computer simulations were in good agreement with the potentials generated by the PSM/ICCP model. For the quiescent tests conducted, the potentials predicted by CPBEM and BEASY were generally within 5 percent and 2 percent of the PSM potentials, respectively. For the dynamic tests conducted, both CPBEM and BEASY produced potentials within 5 percent of the PSM potentials.

Both the PSM and computer simulation test results indicate that an area of marginal protection occurs behind the propellers if the mid-aft reference electrode is used to control the aft anode current output. By positioning the feedback reference electrode aft of the propellers this area of marginal cathodic protection is significantly reduced without increasing the potential over the rest of the structure to levels which would result in paint degradation.

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4 AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj John E) K.J. KarisAllen, C.A. Taweel, K.D. MacKay and D. Brennan		
5 DATE OF PUBLICATION (month and year of publication of document) February 2001	6a NO OF PAGES (total containing information include Annexes, Appendices, etc) 75	6b NO OF REFS (total cited in document) 9
7 DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered) CONTRACTOR REPORT		
8 SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include address) Defence Research Establishment Atlantic PO Box 1012 Dartmouth, NS, Canada B2Y 3Z7		
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ABSTRACT

A comprehensive program was conducted to develop two independent methodologies for generating hull potential profiles for impressed current cathodic protection systems. The two methodologies developed were physical scale modeling and computer simulations using CPBEM and BEASY software suites. Conducting the physical scale modeling trials required upgrading the previously inactive PSM facility. The upgrades included designing and developing a digital communication protocol for the system, controllers for the PSM analog devices and controllers for the ICCP model. A 1/100 scale model of CPF was fabricated and instrumented for comparison with the computer simulations. The results indicated that both CPBEM and BEASY computer simulations were in good agreement with the potentials generated by the PSM/ICCP model. For the quiescent tests conducted, the potentials predicted by CPBEM and BEASY were generally within 5 percent and 2 percent of the PSM potentials, respectively. For the dynamic tests conducted, both CPBEM and BEASY produced potentials within 5 percent of the PSM potentials.

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- impressed current cathodic protection
- corrosion prevention
- boundary element modeling
- physical scale modeling
- Canadian Patrol Frigates

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